Bridging the Climate Adaptation Gap in Agriculture: Stakeholders' Perceptions, Hydrological Impact Models and Effective Solutions

Dissertation

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Hiermit erkläre ich an Eides statt, dass ich die vorliegende Dissertationsschrift selbst verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.

I hereby declare upon oath that I have written the present dissertation independently and have not used further resources and aids than those stated.

Hamburg, den 10.10.2022 Rodrigo Valencia Cotera

Dedicated to humanity as a very small effort to help avoid the climate disaster

"Before researchers become researchers they should become philosophers. They should consider what the human goal is, what it is that humanity should create."

Masanobu Fukuoka
The One Straw Revolution

ABSTRACT

Human-induced climate change has increased the Earth's temperature by approximately 1°C. This shift in global temperatures has caused extensive damage to nature and society and it will continue to do so in the upcoming decades as temperatures are projected to further increase. In Europe, drought events have increased in frequency, intensity, and duration, leading to increased pressure on water resources and agriculture. This is particularly alarming, as agriculture is fundamental to global food security. Agriculture and water are closely related and climate change has turned water management into an even more complicated issue. Therefore, future water management has to be addressed with climate change adaptation. Climate change adaptation, however, is a highly challenging process. Stakeholders and decision makers might lack adequate climate risk perceptions, thus underestimating the need to implement adaptation measures. Additionally, adaptation plans might be missing, deficient, or could propose the implementation of measures with low impact or negative impact; the last is known as maladaptation. Therefore, climate change adaptation requires a careful planning.

The objective of this research is to explore ways to improve and support the climate change adaptation process for the agricultural sector. To achieve that, this dissertation seeks to present evidence of the effectiveness of four different adaptation measures in the agricultural sector to adapt to on-going and future climate change and particularly to improve water management practices. This study started by engaging relevant stakeholders in a qualitative modelling process with the purpose of understanding their climate risk perceptions and document their actions and adaptation plans. Following which, a quantitative system dynamics model was developed and calibrated to test the effectiveness of the adaptation plans on two study regions in Europe. The research took place in two highly similar agricultural regions, North East Lower Saxony in Germany and Seewinkel in Austria. The results of this study are intended to support stakeholders to implement climate change adaptation through science-based decision-making.

The results of the qualitative section of this study show that stakeholders are aware of adaptation measures they could implement, however, there are two main factors delaying adaptation. First, their climate risk perceptions are low and second, the implementation of adaptation requires substantial initial investments, which farmers are not ready to pay for. The results of the quantitative section of this study show that the adaptation measure with the most benefits is to change crops, followed by increasing irrigation efficiency, humification and lastly artificial aquifer recharge. The results also showed that adapting agriculture to climate change has numerous additional benefits such as preservation of the local water resources, reduction of costs, reduction of energy demand and reduction of indirect GHG emissions.

ZUSAMMENFASSUNG

Der vom Menschen verursachte Klimawandel hat die Temperatur der Erde um etwa 1°C erhöht. Diese geringe Verschiebung der globalen Temperaturen hat der Natur und der Gesellschaft großen Schaden zugefügt und wird dies auch in den kommenden Jahrzehnten tun. In Europa haben Dürreereignisse an Häufigkeit, Intensität und Dauer zugenommen, was zu einem erhöhten Druck auf die Wasserressourcen und die Landwirtschaft führt. Dies ist besonders besorgniserregend, da die Landwirtschaft für die weltweite Ernährungssicherheit von grundlegender Bedeutung ist. Aufgrund der engen Beziehung zwischen Landwirtschaft und Wasser und da der Klimawandel die Wasserbewirtschaftung zu einem noch komplizierteren Thema gemacht hat, muss die künftige Wasserbewirtschaftung mit einer Anpassung an den Klimawandel einhergehen. Die Anpassung an den Klimawandel ist jedoch ein äußerst schwieriger Prozess. Interessenvertreter und Entscheidungsträger nehmen das Klimarisiko möglicherweise nicht ausreichend wahr und unterschätzen daher die Notwendigkeit von Anpassungsmaßnahmen. Darüber hinaus können Anpassungspläne fehlen, unzureichend sein oder die Umsetzung von Maßnahmen mit geringer oder negativer Wirkung empfehlen; letzteres wird als Fehlanpassung bezeichnet. Daher sollte die Anpassung an den Klimawandel nicht ohne eine sorgfältige Planung durchgeführt werden.

Ziel dieser Forschungsarbeit ist es, Möglichkeiten zur Verbesserung und Unterstützung des Anpassungsprozesses an den Klimawandel in der Landwirtschaft zu erforschen. Um dies zu erreichen, soll in dieser Dissertation die Wirksamkeit von vier verschiedenen Anpassungsmaßnahmen im Agrarsektor nachgewiesen und der Wasserbedarf gesenkt werden. Die Studie begann mit der Befragung von Interessengruppen in einem qualitativen Modellierungsprozess, um deren Wahrnehmung von Klimarisiken zu verstehen und ihre Anpassungspläne zu dokumentieren. Anschließend wurde ein quantitatives Modell entwickelt und kalibriert, um die Wirksamkeit der Anpassungspläne in zwei Studienregionen in Europa zu testen. Die Studie besteht aus drei Kapiteln, die den Prozess der Einbeziehung der Interessengruppen, die Modellentwicklung und die Umsetzung des Modells abdecken. Die Studie wurde in zwei sehr ähnlichen landwirtschaftlichen Regionen durchgeführt: Nordostniedersachsen in Deutschland und Seewinkel in Österreich. Die Ergebnisse dieser Studie sollen den Interessengruppen zur Verfügung gestellt werden, um die Anpassung an den Klimawandel durch wissenschaftlich fundierte Entscheidungen zu unterstützen.

Die Ergebnisse des qualitativen Teils dieser Studie zeigen, dass sich die Akteure der Anpassungsmaßnahmen bewusst sind, die sie umsetzen könnten, es jedoch zwei Hauptfaktoren gibt, die die Anpassung verzögern. Erstens ist ihre Wahrnehmung des Klimarisikos gering und zweitens erfordert die Umsetzung von Anpassungsmaßnahmen erhebliche Anfangsinvestitionen, die die Landwirte nicht bereit sind zu zahlen. Die Ergebnisse des quantitativen Teils dieser Studie zeigen, dass die Anpassungsmaßnahme mit dem größten Nutzen die Umstellung von Kulturen ist, gefolgt von der Steigerung der Bewässerungseffizienz, der Humifizierung und schließlich der künstlichen Anreicherung von Grundwasser. Die Ergebnisse zeigen auch, dass die Anpassung der Landwirtschaft an den Klimawandel zahlreiche zusätzliche Vorteile hat, wie z. B. den Erhalt der lokalen Wasserressourcen, die Senkung der Kosten, die Verringerung des Energiebedarfs und die Reduzierung der indirekten Treibhausgasemissionen.

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LIST OF PUBLICATIONS

The three main chapters of this dissertation have been published, submitted or are to be submitted to peer-reviewed scientific journals.

Chapter Number	Title	Authors	Status	Journal	Impact Factor
2.	*Identifying Strengths and Obstacles to Climate Change Adaptation in the German Agricultural Sector: A Group Model Building Approach*	Valencia Cotera, Rodrigo Egerer, Sabine Máñez Costa, María	Published (2022)	Sustainability	3.25
3.	*An Assessment of Water Management Measures for Climate Change Adaptation of Agriculture in Seewinkel*	Valencia Cotera, Rodrigo Guillaumot, Luca Sahu, Reetik-Kumar Lierhammer, Ludwig Nam, Christine Máñez Costa, María	Submitted	Science of the Total Environment	7.96
4.	*An Assessment of Water-Management Based Climate Change Adaptation in Lower Saxony*	Valencia Cotera, Rodrigo Egerer, Sabine Lierhammer, Ludwig Nam, Christine Moors, Lukas Máñez Costa, María	To be submitted	Journal of Water and Climate Change	2.8

Other publications not included in this dissertation

Peer-reviewed scientific journals

- Egerer, S., **Valencia Cotera, R.**, Máñez Costa, M. (2021). A leverage points analysis of a qualitative system dynamics model for climate change adaptation in agriculture. *Agricultural Systems,* 189.

DECLARATION OF AUTHORSHIP

Rodrigo Valencia Cotera
Born in Monterrey, Mexico on the 18th of February, 1988

I hereby declare my share in the authorship of the dissertation chapters (research articles), which are either published, submitted, or are to be submitted to peer-reviewed journals, as following:

Chapter	Title	First author contribution (Rodrigo Valencia Cotera)	Co-authors contributions
2.	*Identifying Strengths and Obstacles to Climate Change Adaptation in the German Agricultural Sector: A Group Model Building Approach*	**Methodology** (partially) **Investigation** (partially) **Writing-original draft** (completely)	**Methodology** María Máñez Costa, Sabine Egerer **Investigation** Sabine Egerer **Writing-review and editing** María Máñez Costa, Sabine Egerer **Funding acquisition** María Máñez Costa
3.	*An Assessment of Water Management Measures for Climate Change Adaptation of Agriculture in Seewinkel*	**Conceptualization** (predominantly) **Data Curation** (predominantly) **Formal Analysis** (completely) **Investigation** (completely) **Methodology** (completely) **Software** (completely) **Writing-original draft** (completely)	**Conceptualization** Luca Guillaumot, Reetik-Kumar Sahu **Data Curation** Luca Guillaumot, Ludwig Lierhammer **Writing-review and editing** Luca Guillaumot, Reetik-Kumar Sahu, Christine Nam, María Máñez Costa

4.	*An Assessment of Water-Management Based Climate Change Adaptation in Lower Saxony*	**Conceptualization** (completely) **Data Curation** (predominantly) **Formal Analysis** (completely) **Investigation** (predominantly) **Methodology** (completely) **Software** (predominantly) **Writing-original draft** (completely)	**Data Curation** Ludwig Lierhammer Sabine Egerer **Investigation** Sabine Egerer **Software** Lukas Moors **Writing-review and editing** Sabine Egerer Ludwig Lierhammer Christine Nam María Máñez Costa

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ABBREVIATIONS

AR5	Fifth Assessment Report
BAU	Business As Usual
EU	European Union
FCM	Fuzzy Cognitive Mapping
GHG	Greenhouse gas
GMB	Group Model Building
GVA	Gross Value Added
IPCC	Intergovernmental Panel on Climate Change
IWD	Irrigation Water Demand
NELS	North East Lower Saxony
NGO	Non-Governmental Organization
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
SD	System Dynamics
WDM	Water Demand Management

CHAPTER 1: *Introduction*

1.1 INTRODUCTION

The negative impacts of the Industrial Revolution have been catastrophic for nature and humanity. Since the industrialization, human activities have emitted enormous amounts of CO_2 and other greenhouse gases (GHG) into the atmosphere. In 2019, annual GHG emissions reached 58.1 GtCO2e (UNEP, 2021). The accumulation of these gases in the atmosphere has currently caused approximately 1.0°C of global warming compared to pre-industrial levels (IPCC, 2018). This apparently small, yet meaningful, shift in global temperatures has caused extensive losses and damages to nature and society, and it has led to irreversible impacts (IPCC, 2022c).

During the 1980s, climate models were improved and the scientific community became more certain that global temperatures would increase by several degrees during the 21st century. Since then, the scientific community has issued warnings and requests to urgently cut down emissions. Famous early warnings from the scientific community include Carl Sagan's testimony before the US Congress in 1985 and Dr. James E. Hansen's testimony before the US Senate in 1988 (Shabecoff, 1988). During his testimony, Hansen presented and discussed evidence that the human signal in climate change had been detected (Hansen et al., 1988). His model accurately predicted climate change trends, estimating that by 2020 the net greenhouse forcing would be 1°C. The paper even discussed differences in spatial distribution of decadal temperature changes and the possible increase in the frequency of extreme weather events caused by climate change.

However, even when warnings came long before the consequences of climate change were noticeable, government bodies and the private sector have failed to seriously consider these warnings and to act accordingly. The energy sector has even hidden evidence from the public, openly denied evidence or downplayed the effects of climate change (Frumhoff et al., 2015). One example of this is Exxon Corporation, which deliberately and systematically promoted climate change denial through propaganda and misleading statements (Supran & Oreskes, 2021). Climate change denial led to slow action and ever-increasing GHG emissions. Evidence of this is the fact that more than 50% of all GHG emissions were emitted since 1988 (Frumhoff et al., 2015) and emissions continue to grow every year. Between 2010 and 2019 emissions grew by 1.3% each year (UNEP, 2021).

Climate change is expected to exacerbate the extinction rate of terrestrial species and reduce their geographical range. At a global warming level of 1.5°C, 3 to 14% of the assessed species will likely face a very high risk of extinction increasing up to 39% at 4°C (IPCC, 2022c). Climate change will also reduce the geographical range of 18% of insects, 16% of plants and 8% of vertebrates at 2°C (IPCC, 2018). In biodiversity hotspots, species have a very high risk of extinction. The risk will increase to a tenfold if warming rises from 1.5°C to 3°C (IPCC, 2022c). In aquatic ecosystems a global warming of 2°C is expected to put ecosystems at a high to very high risk (IPCC, 2022c) and to bleach >99% of the coral reefs of the world (IPCC, 2018).

Climate change has also increased the frequency and intensity of extreme weather events like hot extremes, droughts and heavy precipitation (IPCC, 2022a; Samaniego et al., 2018). The increase in the intensity and frequency of extreme weather events like droughts, hot extremes, and heavy precipitation events are associated with substantial financial, human, and environmental impacts (IPCC, 2022c). The increase and frequency of extremes will increase the risks to food security. Climate change will undermine food production as it will cause issues such as weakening soil health and pests (IPCC, 2022c). Of all climate extremes, droughts and heat extremes are particularly concerning for the agricultural industry, as 82% of all damage caused by droughts is absorbed by agriculture (FAO, 2021).

In Europe, drought events have become more frequent and intense in the last thirty years (Stein et al., 2016) and its effects on agriculture have already become noticeable. Between 1981 and 2010, droughts caused average losses of €9.0 billion per year and raging between €7.4 to 14.2 billion per year (Cammalleri et al., 2020). Between 39–60% of the damage caused by droughts in Europe relate to the agricultural sector (Cammalleri et al., 2020) and it is estimated that cereal losses increase 3 % per year due to drought (Brás et al., 2021). Climate change will further threaten food security as it will reduce wheat production by 6% for each degree Celsius of temperature increase (Asseng et al., 2015). Additionally, climate change is expected to further alter the water balance in Europe, thus drought damage could further increase (Naumann et al., 2019; Samaniego et al., 2018).

Historically, Germany has been considered a water-rich region, however, an increase in drought events has been observed since the 1980s with noticeable events in 2003, 2007, 2011 (EEA, 2012) and recently in 2018 and 2019 (Ionita, 2020). One particularly concerning extreme weather event was the drought of 2018. During that year, Germany experienced the hottest and driest conditions since the measurements began in 1881 (Zscheischler & Fischer, 2020). The losses incurred from the drought of 2018 are estimated to be €3.3 billion, making it the costliest single-year weather event in Europe (Ionita, 2020). The increase in heatwaves is especially concerning to Lower Saxony as it is one of the most important agricultural regions in Germany and the region heavily depends on irrigation. More than 50% of the irrigated agricultural land in Germany is located in Lower Saxony and two thirds of it are located in North East Lower Saxony (NELS) (Ostermann, 2019). The region has currently no water issues but the irrigation water demand more than doubled during the drought of 2018, which raised questions about whether agricultural practices in the region are sustainable in the face of climate change.

This trend has also been observed in other European countries such as Austria. Austria is also a water rich country where the renewable freshwater resources significantly exceed water use (Haas & Birk, 2019). The frequency of extreme weather events in Austria is also increasing and the country has recently experienced drought events in the years 2003, 2015 and 2018 (Lindinger et al., 2021). Currently, the agricultural losses caused by drought in Austria are higher than the combined losses due to hail, floods, storms, and frost (Leitner et al., 2020). Additionally, West Austria is particularly dry in comparison to the east. Therefore, it is expected that the water demand for irrigation will increase in the future from west to east (Lindinger et al., 2021). Important agricultural regions like Marchfeld and Seewinkel are located in the west of Austria. Both regions have already experienced some sort of water related issue. In Marchfeld, groundwater levels dropped 2.5 m between 1945 and 1995 (Christoph, 2019) and in Seewinkel the salt lakes area reduced from 3,600 ha in 1858 to only 660 ha in 2006, which implies a loss of almost 82% of this unique natural habitat (Rechnungshof Österreich, 2020).

Climate change is turning water management for agriculture into an even more complex task; climate adaptation will therefore be critical to ensure effective water management (Iglesias & Garrote, 2015). In addition, climate change adaptation is especially important for agriculture to ensure food security (EEA, 2019; IPCC, 2022c) but it also has additional benefits as it improves agricultural productivity (IPCC, 2022c), strengthens the preservation of water resources (Turral et al., 2011), and promotes soil conservation (EEA, 2019). Climate change adaptation, however, is a delicate process that requires rigorous planning as adaption measures could result in trade-offs (IPCC, 2019) and can ultimately lead to maladaptation. Maladaptation refers to the result of poorly designed measures but more specifically to measures, which actually worsen the situation (Schipper, 2020). Maladaptation increases vulnerability to climate change by rebounding vulnerability on the implementing actor, shifting vulnerability to other actors or by degrading the common pool of resources (Juhola et al., 2016; Neset et al., 2018).

Maladaptation can be avoided by planning and developing long-term measures and policies, which consider the effects on different groups, sectors and across scales (IPCC, 2022a, 2022b). Implementing climate change adaptation without first understanding how climate change interacts with socio-ecological stressors, such as, what makes different groups vulnerable and how the vulnerability is distributed across scales, may unintentionally lead to new vulnerabilities or diminish existing adaptive capacities (Burnham et al., 2018). In this light, the inclusion of stakeholder knowledge is paramount for adaptation planning (UN Environment Programme, 2021) as it promotes dialogue and knowledge exchange between groups. Additionally, there is substantial evidence showing that the willingness and ability of farmers to adapt to climate change depends on their awareness about climate change and the perceived risks (Abid et al., 2019; Aidoo et al., 2021; Hundera et al., 2019; Jha & Gupta, 2021; Li et al., 2021; Mahmood et al., 2021; Mase et al., 2017; Snaibi et al., 2021). Therefore, including relevant sectors and their actors in the adaptation process is beneficial as it can spread awareness about their shared climate change risks.

The climate change adaptation process should anticipate and evaluate the potential trade-offs caused by response actions and their effect across scales (IPCC, 2019; UN Environment Programme, 2021). While information on adaptation measures is commonly available and accessible, evidence on the effectiveness of adaptation measures at a local scale is usually missing. This is particularly important as adaptation measures are not equally effective across regions and each region has unique structures and requirements. These unique structures can lead to adaptation measures being less effective, impractical or even unfeasible. Therefore, analyzing the effectiveness of adaptation measures is paramount to select and rank adequate measures, while ensuring that the measures are feasible, do not increase vulnerability, and cover the stakeholders' needs. Doing this is crucial to develop successful regional adaptation plans for agriculture, particularly with respect to water management.

1.2 RESEARCH OBJECTIVE

The overall objective of this research is to understand the effectiveness of adaptation measures for the agricultural sector, in order to support decision makers to develop adequate climate change adaptation plans. This thesis presents the development and implementation of a modeling approach that examines the causal relationships between agriculture and local water resources to evaluate the long-term effectiveness of climate change adaptation measures. The overall aim of this research is

to provide evidence of the effectiveness of adaptation measures for the agricultural sector in order to support decision makers to develop adequate climate change adaptation plans for North East Lower Saxony, Germany and Seewinkel, Austria.

To achieve the main objective, the thesis answers the following research questions:

RQ1. What is the current state of climate change adaptation in NELS?

RQ1.1 How do stakeholders perceive climate change and drought?

RQ1.2 Are systemic adaptation measures being developed and implemented?

RQ1.3 What are the region's key vulnerabilities and possible challenges for adaptation?

RQ2. How effective are adaptation measures to ensure the viability of agriculture under climate change in NELS and Seewinkel?

RQ2.1 Which adaptation measures can better adapt agriculture to climate change without increasing its water demand?

RQ2.2 What are the additional benefits of implementing climate change adaptation measures?

1.3 THESIS STRUCTURE AND RESEARCH METHODS

This study predominantly relied on qualitative and quantitative System Dynamics (SD) methods to answer the research questions stated in Section 1.2. Jay W. Forrester of the Massachusetts

Institute of Technology developed SD in the 1950s as a method to simulate the behavior of non-linear systems using stocks, flows, and feedback loops. Since then, SD has proven to be a useful method, which allows us to understand the structure and dynamic behavior of complex systems. SD consists of two approaches: a qualitative and a quantitative. Qualitative SD, also called causal-loop diagrams, is a useful method to capture and describe the structure of complex systems and the relationships within them. Quantitative SD, also known as stocks and flows diagrams, is an advantageous modeling method that can be used to perform computer simulations of complex systems and use them to develop policies that are more effective (Sterman, 2000). Usually, causal loop diagrams are developed first to describe the structure of the system. Afterwards, the causal loop diagram is transformed into a quantitative stock and flow model to perform numerical simulations. In this thesis, both methods were implemented.

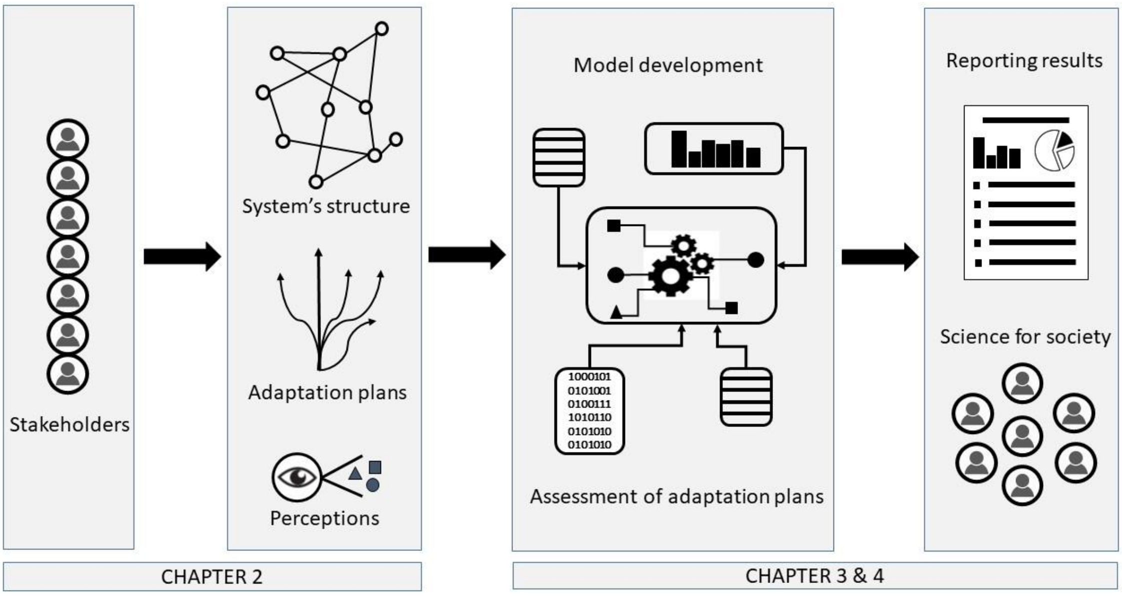

Figure 1.1 Structure of the research method. In Chapter 2 the stakeholders' perceptions, their adaptation intentions and the structure of the system was captured using Group Model Building. In Chapter 3 and 4 a system dynamics impact model was developed and calibrated to test climate change adaptation measures suggested by stakeholders or currently being discussed in the region.

The main reason behind the selection of SD as the research method is that climate change is a wicked problem (Sun & Yang, 2016) and it has even been described as *the wicked problem per excellence* (Termeer et al., 2013). Wicked problems arise as symptoms of other problems, are difficult to formulate, and their solutions are not conclusive (Webber, 1973). Oftentimes, they can cause new and unforeseen problems (Sun & Yang, 2016). In this context, this study is based on the standpoint that climate change, and more specifically, climate change adaptation should be approached from a systemic point of view. Therefore, the development of climate change adaptation plans should be based on adaptation measures, which have been tested to prove their effects and efficiency at a systemic level.

This study implemented a SD approach based on this principle. Figure 1.1 shows the research design and methods. First, a participatory SD modeling approach with stakeholders was carried out. During the participatory approach a causal loop diagram describing the structures of the system was co-developed with stakeholders. The information gathered during that exercise was later used to develop a SD impact model based using stocks and flows. The model was later used to test different adaptation scenarios suggested by stakeholders during the participatory modelling exercise.

1.3.1 Summary Chapter 2: Identifying Strengths and Obstacles to Climate Change Adaptation in the German Agricultural Sector: A Group Model Building Approach.

Chapter 2 is based on Group Model Building (GMB) (Vennix, 1996). GMB is a participatory method used to engage stakeholders in the co-development of system dynamics models. By engaging stakeholders, it is possible to access the mental database. The mental database refers to the information stored in people's minds. The benefit of accessing the mental database is that the amount of information stored in the mental models is vast if compared to data stored in numerical and written databases (Sterman, 2000).

As previously mentioned, there is extensive evidence suggesting that farmer's climate change perceptions and awareness significantly influence their adaptation planning and implementation. However, no previous studies, which captured the perception and adaptation intentions of farmers in North East Lower Saxony were found. Therefore, the study presented in Chapter 2 was implemented to fill this research gap. The main objective of Chapter 2 is to

evaluate the preparedness of the region to find possible knowledge gaps in order to support climate adaptation in NELS and as well as the development of customized climate services

The information gathered during the GMB exercise answers the first research question. The GMB process provided a detailed description of the systemic structures in NELS governing the behavior of agricultural systems and its relation to water resources. Additionally, it was possible to capture the stakeholders' perception and their climate adaptation intentions.

1.3.2 Summary Chapter 3: An Assessment of Water Management Measures for Climate Change Adaptation of Agriculture in Seewinkel.

In this chapter a qualitative system dynamics approach was implemented to develop an original hydrological impact model. The model depicts the interactions between agriculture, water resources and the climate. The model was developed for Seewinkel, an important agricultural region in Austria. This impact model was then calibrated with observational data including weather stations data and water level data from the aquifer and lakes. Afterwards, the calibrated model was forced with an ensemble of regional climate model data from the EURO-CORDEX initiative for three Representative Concentration Pathways (RCP) scenarios (RCP 2.6, 4.5 and 8.5). Using the model, three adaptation measures were tested and compared. These measures are based on information collected with a participatory approach implemented by Kropf et al. (2021).

There are two common knowledge gaps found in water management. First, the inadequate understanding of causal loop relationships in the system (Strosser et al., 2012). Second, the development of water management measures using historical data, assumes that hydrological systems are stationary (Ludwig et al., 2014). Therefore, to breach these gaps and appropriately implement climate change adaptation through water management strategies, an evaluation of adaptation measures with top-down impact models is required (Ludwig et al., 2014; Montanari et al., 2013). In this chapter, an impact model was developed to test adaptation measures and to cover these knowledge gaps. Doing this, the study provides information on the effects of adaptation measures on the system and on their effectiveness. The goal of this study is to

support evidence-based decision-making in Seewinkel by reducing the uncertainty about the efficacy of adaptation measures and to encourage the conservation of local water resources and promote food security.

1.3.3 Summary Chapter 4: An Assessment of Water Management-Based Climate Change Adaptation in Lower Saxony.

Chapter 4 is based on the same objectives as Chapter 3. This time however, the analysis was carried out in NELS. The hydrological impact model developed in Chapter 3 was improved and then recalibrated for the county of Uelzen; an agricultural county in NELS heavily relying on irrigation. The model was once again forced with EURO-CORDEX data. Four adaptation measures were again tested and compared. Stakeholders suggested these adaptation measures during the participatory approach implemented in Chapter 2. The results of Chapter 3 and Chapter 4 were used as evidence to answer the second research question. Therefore, the goal of the study presented in this chapter is to

support evidence-based decision-making in Uelzen by reducing the uncertainty about the efficacy of adaptation measures and to encourage the conservation of local water resources and promote food security.

1.4 CASE STUDIES

This study was conducted in two study regions. The first one being North East Lower Saxony (NELS) in Northern Germany and the second one Seewinkel in Austria. NELS and Seewinkel are important agricultural regions in their respective countries. These regions share similar characteristics, which make them ideal for a comparative study. Some of their shared characteristics include similar crops, a high reliance on irrigation, identical irrigation methods, extraction of groundwater for irrigation, and an annual average precipitation of 600 mm.

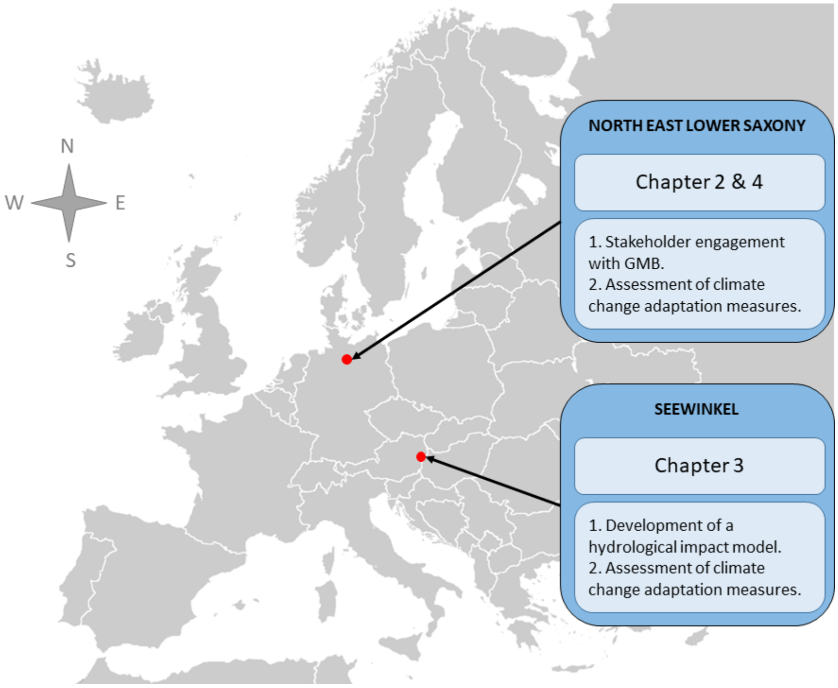

Figure 1.2 Study areas in Germany and Austria.

NELS includes the county of Harburg, Soltau, Lüneburg, Uelzen, Lüchow-Dannenberg and the south of Rotenburg County. Within NELS (10,731 km2) around 47% of the land is used for agriculture (Grocholl, 2011; Umweltbundesamt, 2018) and agriculture represents 2,39% of the gross value added (GVA); a high percentage when compared with the 0,85% at national level (Grocholl, 2011). NELS is characterized by sandy soils with an extremely poor water retention capacity. The region is also the only dry subcontinental lowland region in Lower Saxony (KLIMZUG-NORD Verbund, 2014). Despite that, the region is specialized in growing potatoes, sugar beets and vegetables, all of which are water-demanding crops. These characteristics make the region dependent on irrigation and make it susceptible to yield reduction in the case of water shortages (LWK Niedersachsen, 2012). Because of this, since the 1950s, farmers have invested on irrigation systems in the area due to crop failure caused by drought. It is estimated that 90% of the agricultural land in the area has some sort of irrigation system and the water is mainly extracted from aquifers (LWK Niedersachsen, 2008). In addition to the natural rainfall of around 600 mm per year, the fields are irrigated, on average, with around 60 to 80 mm of water per year (LWK Niedersachsen, 2012).

Comparably, Seewinkel is a semi-arid region (Mitter & Schmid, 2021a) located west of the Lake Neusiedl in the state of Burgenland, Austria. Seewinkel is around 450 km2, has average annual precipitation of 600 mm (Kropf et al., 2021). Local agriculture relies on irrigation and it uses the majority of the land in Seewinkel for cropland (56%), for grassland (6%), and for vineyards (10%) (Karner et al., 2019). The local agricultural industry extracts irrigation water from a single aquifer and farmers irrigate using two methods: sprinkler systems for the crops and drip irrigation for the vineyards. Local produce includes sugar beets, corn, potatoes, soy, cereals, and sunflower (Mitter & Schmid, 2021b). Regional agriculture shares the land with saline lakes called “Salzlacken”. The saline lakes are a fragile ecosystem connected to the groundwater (Magyar et al., 2021). Preserving the saline lakes is of vital importance as they are a habitat for amphibians, birds and florae (Krachler et al., 2012). This implies that a significant drop in groundwater levels could destroy these ecosystems, as a minimum input of ground water is necessary to maintain their chemical balance (Krachler et al., 2012). Since the beginning of the 20th century, many of these lakes were heavily modified. Because of its status as semi-arid region, Seewinkel is at risk of increasing water stress caused by climate change and aggravated by human activities (Magyar et al., 2021).

REFERENCES

Abid, M., Scheffran, J., Schneider, U. A., & Elahi, E. (2019). Farmer Perceptions of Climate Change, Observed Trends and Adaptation of Agriculture in Pakistan. *Environmental Management*, *63*(1), 110–123. https://doi.org/10.1007/s00267-018-1113-7

Aidoo, D. C., Boateng, S. D., Freeman, C. K., & Anaglo, J. N. (2021). Heliyon The effect of smallholder maize farmers ’ perceptions of climate change on their adaptation strategies : the case of two agro-ecological zones in Ghana. *Heliyon*, *7*(April), e08307. https://doi.org/10.1016/j.heliyon.2021.e08307

Asseng, S., Ewert, F., Martre, P., Rötter, R. P., Lobell, D. B., Cammarano, D., Kimball, B. A., Ottman, M. J., Wall, G. W., White, J. W., Reynolds, M. P., Alderman, P. D., Prasad, P. V. V., Aggarwal, P. K., Anothai, J., Basso, B., Biernath, C., Challinor, A. J., De Sanctis, G., … Zhu, Y. (2015). Rising temperatures reduce global wheat production. *Nature Climate Change*, *5*(2), 143–147. https://doi.org/10.1038/nclimate2470

Boonstra, J. (1994). Estimating Peak Runoff Rates. In *The Handbook of Applied Hydrology* (pp. 121–144). McGraw Hill New York.

Bos, M. G., Kselik, R. A. L., Allen, R. G., & Molden, D. J. (2009). Effective Precipitation. In *Water Requirements for Irrigation and the Environment* (pp. 81–101). Springer. https://doi.org/https://doi.org/10.1007/978-1-4020-8948-0

Brás, T. A., Seixas, J., Carvalhais, N., & Jagermeyr, J. (2021). Severity of drought and heatwave crop losses tripled over the last five decades in Europe. *Environmental Research Letters*, *16*(6). https://doi.org/10.1088/1748-9326/abf004

Brouwer, C., & Heibloem, M. (1986). *Irrigation Water Management: Irrigation Water Needs. Training Manual no. 3*. FAO.

Burek, P., Satoh, Y., Kahil, T., Tang, T., Greve, P., Smilovic, M., & Guillaumot, L. (2020). Development of the Community Water Model (CWatM v1 . 04) – a high-resolution hydrological model for global and regional assessment of integrated water resources management. *Geoscientific*

Model Development, *13*, 3267–3298.
Burnham, M., Rasmussen, L. V., & Ma, Z. (2018). Climate change adaptation pathways: Synergies, contradictions and tradeoffs across scales. *World Development*, *108*, 231–234. https://doi.org/10.1016/j.worlddev.2018.04.014
Cammalleri, C., Naumann, G., Mentaschi, L., Formetta, G., Forzieri, G., Gosling, S., Bisselink, B., De Roo, A., & Feyen, L. (2020). Global warming and drought impacts in the EU. *Publications Office of the European Union*. https://doi.org/10.2760/597045
Christoph, J. (2019). Journal of Hydrology : Regional Studies Trends in Austrian groundwater – Climate or human impact ? *Journal of Hydrology: Regional Studies*, *22*(January). https://doi.org/10.1016/j.ejrh.2019.100597
EEA. (2012). *Climate change, impacts and vulnerability in Europe 2012* (Issue 12).
EEA. (2019). *Climate change adaptation in the agriculture sector in Europe*. *04/2019*.
FAO. (2021). The impact of disasters and crises on agriculture and food security: 2021. In *The impact of disasters and crises on agriculture and food security: 2021*. https://doi.org/10.4060/cb3673en
Frumhoff, P. C., Heede, R., & Oreskes, N. (2015). The climate responsibilities of industrial carbon producers. *Climatic Change*, *132*(2), 157–171. https://doi.org/10.1007/s10584-015-1472-5
Grocholl, J. (2011). *Effiziente Wassernutzung im Ackerbau Nord-Ost-Niedersachsens : Möglichkeiten zur Anpassung an den prognostizierten Klimawandel*. https://www.lwk-niedersachsen.de/index.cfm/portal/6/nav/203/article/16132.html
Haas, J. C., & Birk, S. (2019). *Studies Trends in Austrian groundwater – Climate or human impact ? 22*(January). https://doi.org/10.1016/j.ejrh.2019.100597
Hansen, J., Fung, I., Lacis, A., Rind, D., Lebedeff, S., Ruedy, R., & Russell, G. (1988). Global Climate Change as Forecast by Goddart Institute for Space Studies Three-Dimensional Model. *Journal of Geophysical Research*, *93*(D8), 9341–9364. https://doi.org/10.1029/JD093iD08p09341
Howell, T. A. (2003). Irrigation Efficiency. In *Encyclopedia of Water Science*. Marcel Dekker, Inc. https://doi.org/10.1081/E-EWS 120010252
Hundera, H., Mpandeli, S., & Bantider, A. (2019). Smallholder farmers ' awareness and perceptions of climate change in Adama district , central rift valley of Ethiopia. *Weather and Climate Extremes*, *26*, 100230. https://doi.org/10.1016/j.wace.2019.100230
Iglesias, A., & Garrote, L. (2015). Adaptation strategies for agricultural water management under climate change in Europe. *Agricultural Water Management*, *155*, 113–124. https://doi.org/10.1016/j.agwat.2015.03.014
Ionita, M. (2020). On the curious case of the recent decade , mid-spring precipitation de fi cit in central Europe. *Npj Climate and Atmospheric Science*, 1–10. https://doi.org/10.1038/s41612-020-00153-8
IPCC. (2018). *Global Warming of 1.5 ° C an IPCC special report on the impacts of global of 1.5 °C above pre-industrial levels* (Issue October 2018). http://www.ipcc.ch/report/sr15/
IPCC. (2019). Climate Change and Land. In *An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*.
IPCC. (2022a). Chapter 2: Terrestrial and Freshwater Ecosystems and their Services. In *Sixth Assessment Report*.
IPCC. (2022b). Chapter 5: Food, Fibre, and other Ecosystem Products. In *Sixth Assessment Report*.
IPCC. (2022c). *Climate Change 2022 Impacts, Adaptation and Vulnerab. Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*.
Jha, C. K., & Gupta, V. (2021). Environmental and Sustainability Indicators Farmer ' s perception and factors determining the adaptation decisions to cope with climate change : An evidence from rural India. *Environmental and Sustainability Indicators*, *10*(March), 100112. https://doi.org/10.1016/j.indic.2021.100112
Juhola, S., Glaas, E., Linnér, B.-O., & Neset, T.-S. (2016). Redefining maladaptation. *Environmental Science and Policy*, *55*, 135–140. https://doi.org/10.1016/j.envsci.2015.09.014

Karner, K., Mitter, H., & Schmid, E. (2019). The economic value of stochastic climate information for agricultural adaptation in a semi-arid region in Austria. *Journal of Environmental Management*, *249*(August), 109431. https://doi.org/10.1016/j.jenvman.2019.109431

KLIMZUG-NORD Verbund. (2014). *Kursbuch Klimanpassung - Handlungsoptionen für die Metropolregion Hamburg*. TuTech Agentur. www.klimzug-nord.de

Krachler, R., Korner, I., Kirschner, A., Dvorak, M., Milazowszky, N., Rabitsch, W., Werba, F., & Zulka, K. P. (2012). *Die Salzlacken des Seewinkels: Erhebung des aktuellen ökologischen Zustandes sowie Entwicklung individueller Lackenerhaltungskonzepte für die Salzlacken des Seewinkels (2008 – 2011)*.

Kropf, B., Schmid, E., & Mitter, H. (2021). Multi-step cognitive mapping of perceived nexus relationships in the Seewinkel region in Austria. *Environmental Science and Policy*, *124*(April), 604–615. https://doi.org/10.1016/j.envsci.2021.08.004

Leitner, M., Babcicky, P., Schinko, T., & Glas, N. (2020). Climate Risk Management The status of climate risk management in Austria . Assessing the governance landscape and proposing ways forward for comprehensively managing flood and drought risk. *Climate Risk Management*, *30*(October), 100246. https://doi.org/10.1016/j.crm.2020.100246

Li, W., Yuan, K., Yue, M., Zhang, L., & Huang, F. (2021). Climate Risk Management Climate change risk perceptions , facilitating conditions and health risk management intentions : Evidence from farmers in rural China. *Climate Risk Management*, *32*(February), 100283. https://doi.org/10.1016/j.crm.2021.100283

Lindinger, H., Grath, J., Brielmann, H., Schönbauer, A., Gattringer, I., Formanek, C., Broer, M., Rosmann, T., Holler, C., Szerencsits, M., Neunteufel, R., Sinemus, N., Grunert, M., & Germann, V. (2021). Wasserschatz Österreichs. Grundlagen für nachhaltige Nutzungen des Grundwassers Hintergrunddokument. In *Bundesministerium für Landwirtschaft, Regionen und Tourisimus*.

Ludwig, F., Slobbe, E. Van, & Cofino, W. (2014). Climate change adaptation and Integrated Water Resource Management in the water sector. *Journal of Hydrology*, *518*, 235–242. https://doi.org/10.1016/j.jhydrol.2013.08.010

LWK Niedersachsen. (2008). *No Regret - Genug Wasser für die Landwirtschaft?! Projektbericht - Kurzfassung*. zul

LWK Niedersachsen. (2012). *AQUARIUS – Dem Wasser kluge Wege ebnen! Projektbericht*. https://www.lwk-niedersachsen.de/index.cfm/portal/6/nav/203/article/12396.html

Magyar, N., Hatvani, I. G., Arató, M., Trásy, B., Blaschke, A. P., & Kovács, J. (2021). A new approach in determining the decadal common trends in the groundwater table of the watershed of lake "Neusiedlersee." *Water*, *13*(3), 1–17. https://doi.org/10.3390/w13030290

Mahmood, N., Arshad, M., Mehmood, Y., Faisal, M., & Harald, K. (2021). *Climate Risk Management Farmers ' perceptions and role of institutional arrangements in climate change adaptation : Insights from rainfed Pakistan*. *32*(February). https://doi.org/10.1016/j.crm.2021.100288

Mase, A. S., Gramig, B. M., & Prokopy, L. S. (2017). Climate Risk Management Climate change beliefs , risk perceptions , and adaptation behavior among Midwestern U . S . crop farmers. *Climate Risk Management*, *15*, 8–17. https://doi.org/10.1016/j.crm.2016.11.004

Mitter, H., & Schmid, E. (2021a). Informing groundwater policies in semi-arid agricultural production regions under stochastic climate scenario impacts. *Ecological Economics*, *180*(June 2020), 106908. https://doi.org/10.1016/j.ecolecon.2020.106908

Mitter, H., & Schmid, E. (2021b). Informing groundwater policies in semi-arid agricultural production regions under stochastic climate scenario impacts. *Ecological Economics*, *180*(November 2020), 106908. https://doi.org/10.1016/j.ecolecon.2020.106908

Montanari, A., Young, G., Savenije, H. H. G., Hughes, D., Wagener, T., Ren, L. L., Koutsoyiannis, D., Cudennec, C., Toth, E., Grimaldi, S., Blöschl, G., Sivapalan, M., Beven, K., Gupta, H., Hipsey, M., Schaefli, B., Arheumer, B., Boegh, E., Schymanski, S. J., … Belyaev, V. (2013). "Panta Rhei — Everything Flows ": Change in hydrology and society — The IAHS Scientific Decade 2013 – 2022. *Hydrological Sciences Journal*, *58*(6), 1256–1275. https://doi.org/10.1080/02626667.2013.809088

Monteith, J. L. (1965). Evaporation and environment. *Symposia of the Society for Experimental Biology*, *19*, 205–234.
Naumann, G., Cammalleri, C., Mentaschi, L., & Feyen, L. (2019). Increased economic drought impacts in Europe with anthropogenic warming. *Nature Climate Change*. https://doi.org/10.1038/s41558-021-01044-3
Neset, T., Wiréhn, L., Opach, T., Glaas, E., & Linnér, B. (2018). Evaluation of indicators for agricultural vulnerability to climate change : The case of Swedish agriculture. *Ecological Indicators*, *April*, 0–1. https://doi.org/10.1016/j.ecolind.2018.05.042
ORF. (2021). *Land will Donau-Wasser für Seewinkel*. https://burgenland.orf.at/stories/3095447/
Ostermann, U. (2019). Wasserhaushalt in Nordostniedersachsen durch Wassernutzung und -management ausgleichen. *Wasser Und Abfall*, *3*, 39–46.
Rechnungshof Österreich. (2020). *Nationalpark Neusiedler See - Seewinkel*. https://www.rechnungshof.gv.at/rh/home/home/Nationalpark_Neusiedler_See.pdf
Samaniego, L., Thober, S., Kumar, R., Wanders, N., Rakovec, O., Pan, M., Zink, M., Sheffield, J., Wood, E. F., & Marx, A. (2018). Anthropogenic warming exacerbates European soil moisture droughts. *Nature Climate Change*, *8*(5), 421–426. https://doi.org/10.1038/s41558-018-0138-5
Schipper, E. L. F. (2020). Primer Maladaptation: When Adaptation to Climate Change Goes Very Wrong. *One Earth*, *3*(4), 409–414. https://doi.org/10.1016/j.oneear.2020.09.014
Shabecoff, P. (1988). Global Warming Has Begun, Expert Tells Senate. *The New York Times*.
Shen, Y., Li, S., Chen, Y., Qi, Y., & Zhang, S. (2013). Estimation of regional irrigation water requirement and water supply risk in the arid region of Northwestern China 1989 – 2010. *Agricultural Water Management*, *128*, 55–64. https://doi.org/10.1016/j.agwat.2013.06.014
Snaibi, W., Mezrhab, A., Sy, O., & Morton, J. F. (2021). Heliyon Perception and adaptation of pastoralists to climate variability and change in Morocco ' s arid rangelands. *Heliyon*, *7*(November), e08434. https://doi.org/10.1016/j.heliyon.2021.e08434
Stein, U., Ö, G., Tr, J., Landgrebe, R., Szendrenyi, A., & Vidaurre, R. (2016). European Drought and Water Scarcity Policies. In *Governance for Drought Resilience. Land and Water Drought Management in Europe* (pp. 17–44). https://doi.org/10.1007/978-3-319-29671-5
Sterman, J. D. (2000). *Bussiness Dynamics. Systems Thinking and Modeling for a Complex World.* (J. J. Shelstad (ed.)). McGraw-Hill Higher Education.
Strosser, P., Dworak, T., Andrés, P., Delvaux, G., Berglund, M., Mysiak, J., Kossida, M., Iacovides, I., & Ashton, V. (2012). *Gap Analysis of the Water Scarcity and Droughts Policy in the EU European Commission*.
Sun, J., & Yang, K. (2016). The Wicked Problem of Climate Change: A New Approach Based on Social Mess and Fragmentation. *Sustainability*, *8*(12). https://doi.org/10.3390/su8121312
Supran, G., & Oreskes, N. (2021). Rhetoric and frame analysis of ExxonMobil's climate change communications. *One Earth*, *4*(5), 696–719. https://doi.org/10.1016/j.oneear.2021.04.014
Termeer, C., Art Dewulf, & Breeman, G. (2013). Governance of Wicked Climate Adaptation Problems. In *Climate Change Management* (pp. 27–39). Springer, Berlin, Heidelberg. https://doi.org/doi.org/10.1007/978-3-642-29831-8_3
Turral, H., Burke, J., Faures, J. M., & Faures, J. M. (2011). Climate change, water and food security. In *FAO Water Reports*. https://doi.org/ISSN 1020-1203
Umweltbundesamt. (2018). *Struktur der Flächennutzung*. https://www.umweltbundesamt.de/daten/flaeche-boden-land-oekosysteme/flaeche/struktur-der-flaechennutzung#textpart-2
UN Environment Programme. (2021). *Adaptation Gap Report 2020*.
UNEP. (2021). *Emissions Gap Report 2021*.
Vennix, J. A. M. (1996). *Group Model Building: Facilitating Team Learning Using System Dynamics*. John Wiley & Sons Ltd.
Wang, X., Zhang, J., & Ali, M. (2016). *Impact of climate change on regional irrigation water demand in Baojixia irrigation district of China*. 233–247. https://doi.org/10.1007/s11027-014-9594-z
Webber, M. M. (1973). *Dilemmas in a General Theory of Planning **. *4*(December 1969), 155–169.

Zscheischler, J., & Fischer, E. M. (2020). The record-breaking compound hot and dry 2018 growing season in Germany. *Weather and Climate Extremes*, *29*(June), 100270. https://doi.org/10.1016/j.wace.2020.100270

CHAPTER 2: *Identifying Strengths and Obstacles to Climate Change Adaptation in the German Agricultural Sector: A Group Model Building Approach*

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Identifying Strengths and Obstacles to Climate Change Adaptation in the German Agricultural Sector: A Group Model Building Approach

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Abstract: In the past 30 years, there has been a significant increase in drought events in Europe. It is expected that climate change will make droughts more frequent and intense. This situation is particularly concerning for areas with no drought management culture. This study focuses on North East Lower Saxony (NELS), an important agricultural region in northern Germany. We implement a novel approach to Group Model Building to assess the preparedness of NELS to deal with climate change and droughts. Our novel approach includes the creation of a preliminary model based on individual interviews and a triangulation of information after the workshop. We conclude that stakeholders are aware of climate change, but insufficient attention is given to adaptive solutions mainly because they require high initial investments. Given its existing political infrastructure, the region has the potential to adjust. With efficient government bodies are already in place, beneficial updates could be made to established water withdrawal regulations.

Keywords: climate change; climate change adaptation; group model building; agriculture; Lower Saxony; water management

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1. Introduction

Of all climate events, droughts affect the most people around the world [1]. In the past 30 years, there has been an increase in drought events in Europe [2]. Prolonged summer heatwaves and droughts are associated with substantial financial, human, and environmental losses. The losses incurred from the 2018 drought were estimated to be EUR 3.3 billion, making it the costliest single-year weather event in Europe [3]. In Austria, for example, the agricultural losses caused by drought are higher than the combined losses due to hail, floods, storms, and frost [4]. Climate change is expected to increase the intensity and frequency of droughts [5], which could further exacerbate this effect [6]. The situation is particularly concerning for Mediterranean and Western Europe [5,7].

Historically, Germany has been considered a water-rich region and its agriculture is mainly rainfed. Since the 1980s, an increase in drought events has been observed with noticeable events in 2003, 2007, 2011 [8], and lately in 2018 and 2019 [3]. At a national level, climate change is expected to reduce water availability during the growing period. A temperature increase of 3 °C would imply an increase of more than 50% in the annual dry periods [9]. As the effects of climate change become more noticeable, the necessity of climate change adaptation becomes more evident. Government agencies, including the German Environment Agency, have suggested adaptation measures. However, the 2018 drought showed the vulnerability of German agricultural systems and the unpreparedness of governance structures to deal with droughts. To better deal with droughts, the system needs to increase its adaptation capacity and drought resilience.

Understanding how stakeholders perceive climate change can shed light on their behavioral intentions and support climate change adaptation [10,11]. Climate change perceptions are influenced by a multitude of factors including age, gender, political beliefs, education, farm size, emotions and personal experiences [10,12,13]. Perceptions, however, are significantly influenced by the level of education and access to weather and climate information [11,13–15]. There is extensive evidence suggesting that farmer's climate change perceptions and awareness significantly influence their adaptation planning and adoption of adaptation practices [11–13,15–19]. Therefore, implementing an assessment of perceptions is a prerequisite to identify factors that could affect the adaptation process [11,19] of both of agriculture [14] and water resources [20]. The adaptation process can be defined as a three-step process. First, accurate climate risk perceptions; second, adaptation planning and third, implementation of adaptation [11,19].

Additionally, successful water management and climate change adaptation require the participation of numerous stakeholders including policymakers, farmers, NGOs, the private sector, researchers and communities. Their perceptions are crucial to support decision-makers to develop effective policies [12,13,20]. In particular water management benefits from the practical and critical perspectives of all water users [20]. Stakeholder engagement and participatory modeling are useful approaches to promote strategic decision-making for environmental resource management [21]. Participatory modeling also promotes an exchange of information between science and society [22] in which transdisciplinary knowledge exchange takes place.

Group Model Building (GMB) [23] is a useful and efficient method of implementing participatory modeling processes [24]. In GMB, the main objective is to capture the perception of the participating stakeholders on the problem to be solved. The results provide mental models of the participants' perceptions of the problem. However, the main challenge in participatory modeling is to find a way around participants' biases, beliefs, and interests [25]. Therefore, to improve objectivity and comprehensiveness, we propose modifying the GMB suggested by Vennix (1996) [23] to include a preliminary model based on the common perception of the participants and a triangulation process. By triangulation, we mean a combination of methods and comparison of information sources [26]. Through the implementation of our revised GMB approach, we developed causal-loop diagrams [24] together with stakeholders. In this study, we refer to those casual-loop diagrams as "models". We created the models together with each stakeholder in a series of personal interviews and one group workshop. In total, we produced 20 individual models, a preliminary model, a group model, and a qualitative model.

Motivated by the recent drought events, we implemented our revised approach in North East Lower Saxony (NELS), an important agricultural region in Germany. Because droughts are a new phenomenon in northern Europe, we hypothesize that the agriculture industry in NELS might not be adequately prepared to face droughts associated with climate change. To explore this, we have set three research questions to assess the preparedness of NELS. First, how do stakeholders perceive climate change and drought? Second, are systemic adaptation measures being developed and implemented? Third, what are the possible challenges for adaptation in the region? Testing the preparedness of the region will also support the finding of possible knowledge gaps and needs for science-based services to support climate adaptation in the region. In this case, the need for better-customized climate services was one of the main drivers for this research.

Despite the significant number of studies implemented around the world exploring stakeholders' perceptions on climate change [10–12,14–18,27–29], to our knowledge, no previous studies have focused on collecting the perceptions of farmers and other stakeholders in North East Lower Saxony. To fill this gap and support climate change adaptation we implemented this Group Model Building approach.

2. Case Study

This research focuses on NELS (Figure 1), an agricultural region situated in the north of Germany, as this region is representative of other similarly irrigated regions in Northern Europe. Within NELS, 47% of the land (5038.36 km^2) is used for agriculture [30], and agriculture represents 2.39% of the gross value added (GVA). This is a high percentage when compared with the 0.85% at national level [31]. The region is located within the transition zone from Atlantic to continental climate [32,33]. This results in a reduction in precipitation from west to east.

NELS is characterized by sandy soils with extremely poor water retention capacity [31]. Despite light soils and insufficient precipitation during the growing season, the region specializes in growing water-demanding crops such as potatoes, sugar beets, and other vegetables. Because of this, farms since the 1950s have invested heavily in irrigation systems. Irrigation water is almost exclusively extracted from aquifers. The most widespread method of irrigation is the sprinkler gun irrigation system [33,34]. It is important to note that the majority of Germany's irrigated land is located in Lower Saxony and that two thirds of that area is located in NELS [35].

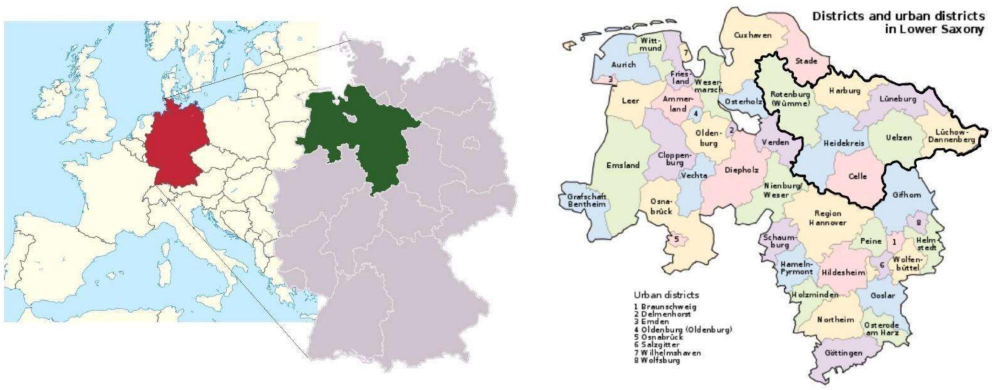

Figure 1. Left: Location of Lower Saxony (green) in Germany (red). Right: Location of NELS inside Lower Saxony. Maps from Egerer et al. (2021) [36].

Multiple studies have demonstrated that climate change will not only increase the temperatures in Lower Saxony but also cause a change in precipitation patterns [37–39]. Scheihing (2019) [39] compared five studies modeling the effect of climate change in Lower Saxony within the reference period (1971–2000). The results show that in Lower Saxony temperatures are expected to increase between 0.6 and 2.2 °C in the middle of the century and increase between 0.6 and 4.9 °C by the end of the century. In the RCP 2.6 scenario, the changes to precipitation are barely detectable. However, in the RCP 8.5 scenario, the yearly average precipitation would increase by 4 to 7 % for the middle of the century, while the summer precipitation would decrease by 6% and winter precipitation would increase by 11%. At a national level, similar trends have already been detected. There has been a pattern of increased winter precipitation and decreased summer precipitation for the period from 1901–2000 for most of the country [40,41].

Observational data (eobs-v19.0e) [42] averaged over NELS show the historical temperature and precipitation trends. For the period 1950–2018, the annual average minimum and maximum temperatures have followed an incremental trend (Figure 2). The total annual precipitation, for the same period, shows a slightly increasing trend while the total precipitation during the growing season (March to August) has followed a slightly decreasing trend (Figure 3). These observations align with the trends identified by Trömel and Schönwiese (2008) [41].

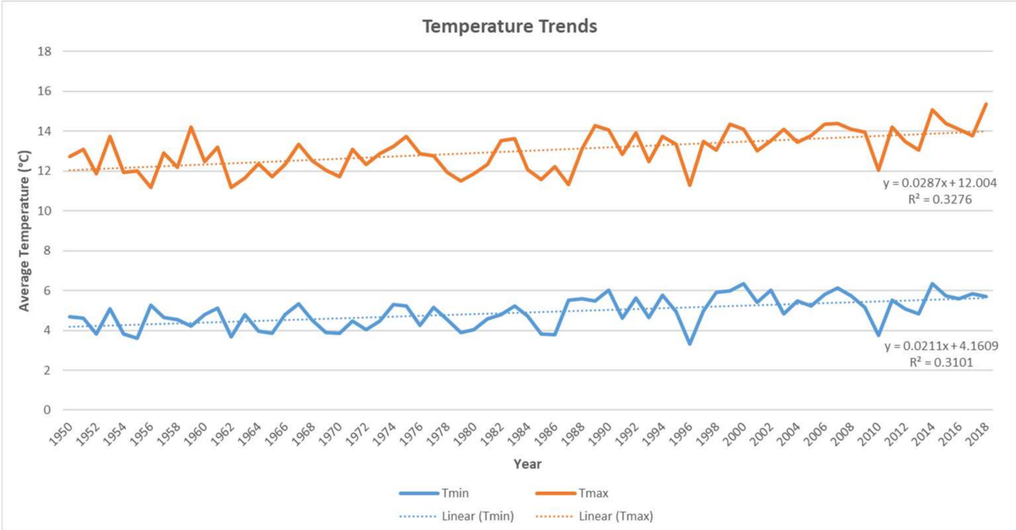

Figure 2. Annual average minimum (blue) and maximum temperature (orange) in NELS for the period 1950–2018.

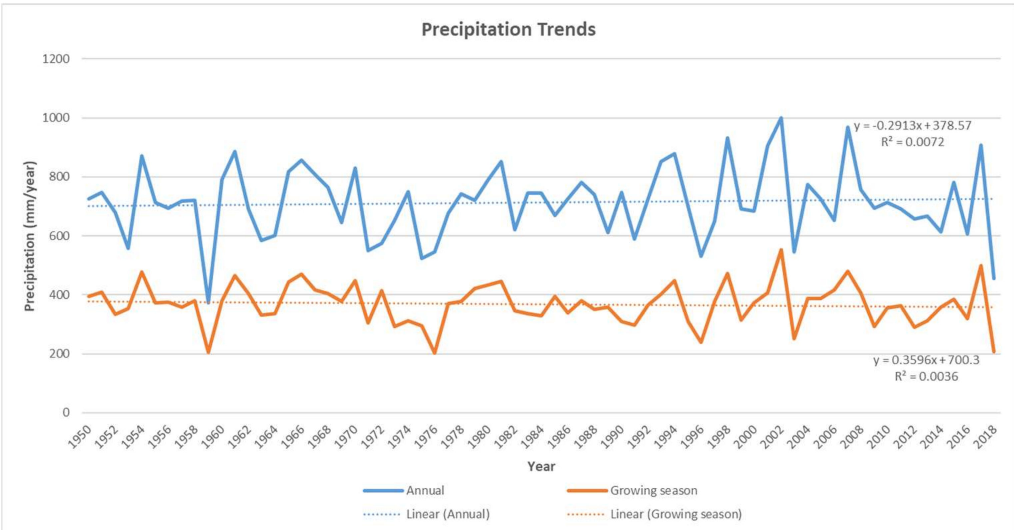

Figure 3. Total annual precipitation (blue) and total precipitation during the growing season (orange) in NELS for the period 1950–2018.

3. Materials and Methods

Due to its complex cross-scale interactions, conflicting inputs, and multiple potential outcomes, climate change has been described as a wicked problem [43]; and climate change adaptation has been termed the "wicked problem par excellence" [44]. Wicked problems are difficult to formulate and arise as symptoms of other problems, their solutions are difficult to identify and they are not conclusive but rather better or worse [45]. Because wicked problems tend to arise at the boundary between humanity and the environment, solutions spawn unforeseen problems [43].

Diverse approaches have emerged to deal with wicked problems, with examples including combining collaborative and process-driven methods [46] or by combining strategic planning theory and Actor-Network-Theory [47]. A more classical approach that has been recognized as a powerful tool to deal with wicked problems is participatory modeling [25]. Participatory Modelling helps to collect the best knowledge about the system in order to understand its causes, drivers and outcomes [25], and portray it using cognitive mapping [48]. In our case, we use participatory modeling to lay the basis for responding to the three previous presented objectives. Through participatory modeling, we mined the mental database of stakeholders who hold institutional memory regarding system structures, policies, and decision-making. The mental database encompasses all the information in people's minds, including their impressions and their understanding of the system and how decisions are taken [49]. This information is usually not available in written databases [50].

One way of implementing participatory modeling is through GMB (Figure 4) developed by Vennix, (1996) [23]. GMB is an effective way of capturing the stakeholders' perceptions and values [51]. Perceptions refers to the way in which people interpret the world by recognizing external stimuli and reacting to them with actions [51]. However, the ultimate goal of a GMB intervention is not only to develop a model of the researched system, but also to delineate a shared understanding of a problem and foster proposed solutions [23] as stakeholders might have different and ambiguous opinions about the problem [52]. GMB is useful when the problem is difficult to identify or when the situation is so complex that no entry point for solutions can be easily identified [53].

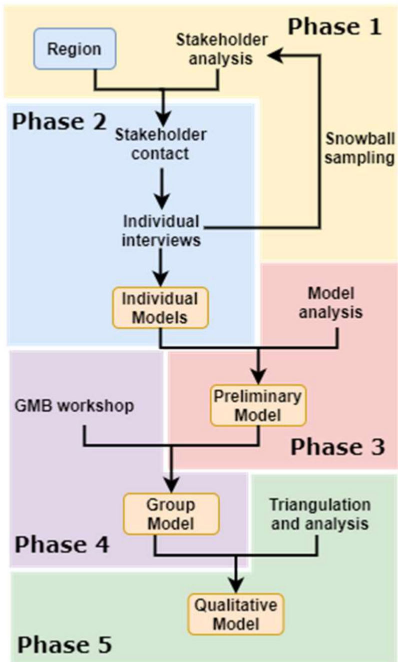

Figure 4. The five stages of our approach to GMB process, from top to bottom. First, the stakeholder analysis phase. Second, the individual interviews producing individual models. Third, the analysis of the individual models to produce the preliminary model. Fourth, the GMB workshop to generate a group model. Fifth, the triangulation and analysis to build the qualitative model.

In addition to its versatility when confronted with complex problems, GMB afforded us a platform to acquire information from a wide range of actors with diverse backgrounds [54]. Multiple studies have presented GMB as an effective tool to gather, record, and share information and as a means to solve complex issues [55–58]. With GMB it is possible to model individual as well as collective perspectives and to include them in the planning process [54]. For example, GMB has been used to anticipate and respond to hydrological events [59], to improve management of coastal areas [60], to plan urban agriculture [54] to model the water-energy-food nexus [24], and to manage wetlands [61].

GMB helped us achieve our first objective (stakeholders' perceptions on climate change and drought) by giving us the opportunity to meet and listen to multiple stakeholders, from farmers and nature protection organizations to water managers and lawmakers and record their perceptions in models. It also helped us to meet our second objective (identify climate change adaptation measures), as the process allowed us to identify individuals and organizations already considering or implementing climate change adaptation measures. It further supported us to meet our third objective (pinpoint barriers to climate change adaptation), as the models serve as a record to be further analyzed. Finally, the process also builds the basis for a possible composite quantitative model.

We have implemented changes to the original method described in Vennix, (1996) [23] and developed a novel approach to GMB (Figure 4) by adding a preliminary model based on individual models and a triangulation process after the group workshop. We propose that these modifications to the method will improve the collection and utilization of information, reduce uncertainty, and compensate for lack of participation during group workshops. These changes should help the modeler achieve a better understanding of the study issue and enhance the model building process. Our approach to GMB is described in the following sections.

3.1. Phase 1: Stakeholder Analysis

A stakeholder analysis is a process used to identify groups, individuals, and organizations affected by a phenomenon in order to prioritize their participation in the decision-making process [62]. These groups, individuals and organizations are referred to as "stakeholders". By including stakeholders in the model development process, models have a higher chance of being accepted, trusted, and used [25]. People who are excluded from the collaborative process might resist the results [23]. Additionally, an individual's understanding of the system is limited in scope. For these reasons, it is necessary to include all relevant actors [63]. It is crucial to consider stakeholder analysis before starting the participatory process [62].

We performed the stakeholder analysis following two approaches: brainstorming in a focus group with experts [62,64] and snowball sampling [62,65]. As explained by Reed, (2009) [62], snowball sampling refers to a method in which individuals from the firstly-identified stakeholder groups help identify new stakeholder categories and contacts. By implementing two methods, our goal was to strengthen stakeholder identification and reduce the chances of leaving important parties out. Since stakeholder identification is usually an iterative process [62], additional participants were identified as the study progressed (see Table 1). Our aim was to strengthen the network and increase group diversity. We decided to include no more than twenty stakeholders as suggested by Vennix (1996) [23].

Table 1. Participants in the study.

Field	Organization
Farmers (n = 8)	Traditional agriculture (n =6) Organic agriculture (n = 2)
Government agencies (n = 8)	Chamber of Agriculture of Lower Saxony (n = 3) Water supply and management agencies (n = 2) Lower Saxony State Department for Water, Coastal and Nature Conservation (n = 1) Ministry of Agriculture (n = 1) Ministry of the Environment (n = 1)
NGOs (n = 2)	Greenpeace (n = 1) BUND (n = 1)
Other organizations (n = 2)	Farmers' association (n = 1) Irrigation association (n = 1)

All participants received a formal invitation to contribute to the project. None of the stakeholders was economically compensated for their participation with the exception of travel expenses to the GMB workshop. None of the stakeholders had experience with system dynamics techniques before their participation in the study. However, all of them had completed basic education, with many of them holding M.Sc. and Ph.D. in their fields of work.

3.2. Phase 2: Individual Interviews

We conducted individual interviews to produce individual qualitative models. We chose a semi-structured interview approach, meaning that the topics and questions were developed beforehand. The wording and sequence of the questions could be adapted in situ while ensuring similar information was collected in every interview. During the approximately two-hour-long individual interview, each stakeholder was directly involved in the creation of an individual model. The stakeholders could, at all times during the interview, see their model as well as add and remove components/variables and adjust the connections between them. At the end of the interview, the stakeholder reviewed and validated their individual model. The objective of individual model building is to refine the perception of each stakeholder in order to accurately represent their personal perspective. Having an individual model also serves as a record in case the participant is unable to attend the group workshop. Additionally, the modelers can deepen their understanding of the issue and prepare for the group workshop.

3.3. Phase 3: Preliminary Model

After the individual interviews were held, we performed a desk analysis of the individual models to develop a preliminary qualitative model based on the gathered information to: (a) gain a general impression of the system's behavior and (b) have a compendium of the stakeholder's personal perceptions. This process of creating a preliminary model is one of our two modifications to Vennix's (1996) [23] GMB method.

Our method to create a preliminary model incorporates (but is not equal to) fuzzy-cognitive mapping (FCM). In FCM, identified concepts and the relationship between them are depicted in a graph, with concepts located in nodes and the relationships between them represented by direct angles. To quantify the influence one component has on the other, weights are assigned to the direct angles, either by expert opinion or empirical data [66]. In our case, we chose our components and gave weight to the connections between them based on the individual models. Each individual model was considered as the expert opinion of a stakeholder.

To speed up the construction of the preliminary model, we developed a Python script to extract and order all variables present in all individual models. The script also created the preliminary model based on boundary conditions. First, the components were automatically arranged in a list ranging from the most frequently occurring to the least frequently occurring. Words which were unmistakable synonyms were grouped together. The script also identified how often a connection between two elements occurred in the individual models.

Afterwards, we fixed the boundary conditions by classifying the components and the relationships between them into tiers. Components which were present in 10 to 20 individual models were classified as Tier-1 components, while components occurring in fewer than 10 models were classified as Tier-2. The same classification was applied to the relationships, though relationships rarely repeat in more than 10 models. Because of this they were classified as Tier-1 (occurring in 10 or more models), Tier-2 (in 7 to 9 models), Tier-3 (in 3 to 6 models), and Tier-4 (in 0 to 2 models).

The preliminary model is composed only of Tier-1 components and Tier-1, Tier-2, and Tier-3 relationships. By including only the components mentioned by the majority of our stakeholders, we created a basic structure to capture the common perception of the system. At the same time, by giving weight to the relationships based on their recurrence in the individual models, we distinguished among interactions: low effect (Tier-1), considerable effect (Tier-2), and strong effect (Tier-3). In the model, thin lines denote a low effect, medium thickness lines denote a considerable effect, and thick lines denote a strong effect. This representation of a common perception of the system aims to reduce subjectivity.

As mentioned above, the preliminary model is created to obtain a general overview of the system, but it is not to function as a final representation of it. Its intention is to help the modeler understand what components and connections are important for the majority of the stakeholders. In other words, the preliminary model represents what the majority of the stakeholders believe is the core of the system and it can be interpreted as a common ground. Additionally, participants had the chance to voice their perceptions in the next step (workshop), ensuring that relevant minority information was not lost.

3.4. Phase 4: Group Model Building Workshop

Following the completion of the preliminary model, we organized a GMB workshop to which all interested parties were invited. In designing the workshop, we followed the four dimensions of GMB as interpreted by Hovmand, (2013) [56]. The result was a GMB workshop with the following dimensions: (1) adaptation of agriculture to climate change was set as the pre-defined problem; (2) the workshop was structured as a group process; (3) the workshop aimed at producing a group model at the end; and (4) the workshop started the process with the "blank slate" approach. Our team consisted of a group facilitator and three notes' recorders [67].

Because presenting a preliminary model may reduce stakeholders' feelings of ownership [23], may bias participants, and may create a framing effect [56], the preliminary model was not shown to stakeholders. Stakeholders engaged in a discussion and information exchange, guided and moderated by a facilitator. The facilitator relied on the model to guide the session and to ensure no valuable information was omitted. As the workshop took place, the relationships and components of the model were confirmed by stakeholder responses to questions posed by the facilitator. During the discussion, new components and relationships were added when agreed by all participants.

Besides describing the researched system, the developed model acted as a boundary object [53,68] as it physically represented dependencies across organizations, disciplines, society, and culture. At the same time, during the workshop, the group model was accessible and modifiable by all stakeholders [69]. The creation of boundary objects is crucial to developing and maintaining coherence across social realms [68]. Boundary objects are particularly useful in the context of GMB [53]. The model facilitates knowledge exchange and agreement among participants, which in turn improves the outcome [53]. Additionally, one of the most common complications in model building happens when one stakeholder group, or the facilitator, dominates the model building or when the facilitator ignores someone's input [53]. In order to avoid this, the interview partners could at all times see the model that was being produced and suggest modifications to the model in any way they thought convenient.

3.5. Phase 5: Triangulation and Analysis

We added a triangulation process as a custom modification to Vennix's GMB method. Usually, a GMB process ends with a group model produced during the group workshop. This might have disadvantages: not all stakeholders will attend the group workshop, the workshop might be unproductive due to differences of opinion, and participation and interest levels will vary. These situations may contribute to a model only partially representing the studied issue. However, we propose that these drawbacks can be overcome by applying triangulation.

Triangulation has been extensively described by Denzin (2009) [70] as a framework for combining methods, data sources, theories, and observations in an investigation. The term also refers to the process of gathering, comparing, and combining information from different sources [26,49]. This includes interviews, literature, previous studies, transcripts of individual or group sessions and personal observations [26]. Observations refer to direct visual observations, as perceptions of the person's mood, non-verbal communication or remarks made when the recorder is off can supply additional valuable information [26]. Additionally, in this study, we include observations made during field trips and visits to local farms and facilities (e.g. biogas plant) in our personal observations. During social research, both data and methods can be triangulated [71,72]. Denzin (2009) [70] recommends the use of triangulation since every research method reveals a specific aspect of empirical reality. Interviews, for example, are almost never sufficient to acquire enough data, since people have only partial and local understanding of the system. Furthermore, interview data is often mixed and it could also include false information [49].

Therefore, it is the task of the modeler to triangulate with as many sources of information as possible to fully understand the structures of the system [49]. The modelers should extract the causal structures from the information provided by stakeholders and should validate the model with archival information (previous studies, reports, legislations and numerical data) as well as their own experience and observations [49]. Through triangulation, we can maximize information completeness while garnering cross-validation [73]. Additionally, objectivity can be difficult to achieve when the research is primarily based on the stakeholders' subjectivity. Each user will respond based on their own past experiences, current mood, and personal idiosyncrasies [70]. Triangulation methods also help achieve an "intersubjective" objectivity [26] and, in most cases, triangulation resolves ambiguity [73].

Based on these parameters, we developed a qualitative system dynamics model representing the structure of the system, built upon the statements given by stakeholders during the interviews and the information captured by the preliminary and group models. First, the water balance of the region was placed as the focal point of the model as as effected by Hassanzadeh al. (2014) [74]. Afterwards, we identified the main causal structures in the preliminary and group models and we verified them with other sources of information coming from numerical and textual databases. The verification or cross-validation process intends to avoid the inclusion of false structures or information in the final model. All information present in the qualitative model can be traced to either the previous models, the literature, or personal observations.

After the completion of the qualitative model, we performed an analysis using the preliminary model, the group model and the qualitative model to answer our three objectives. Because the first two objectives of this research are related to stakeholders' beliefs and behaviors, the preliminary and the group model were used to corroborate their views and engaged them in the model building process. However, to pinpoint the region's possible challenges to climate change adaptation, an additional analysis was required. We based this second examination on the triangulated model.

4. Results and Discussion

This section presents the three models generated during this study plus the results of the analysis made based on our three objectives: (1) Determine how stakeholders perceive climate change and drought. (2) Identify whether systemic adaptation measures are being developed and implemented. (3) Outline possible challenges for adaptation in the region to decrease vulnerability. The models are presented in chronological order and they originate from phases 3, 4, and 5 of this study.

4.1. Perceptions on Climate Change and Drought

The models suggest that the majority of the stakeholders are aware of climate change at least to a certain degree, as both, the preliminary and group models include some reference to climate change. In the preliminary model (Figure 5), the climate considerably affects precipitation but the causes of climate change are not shown. In the group model, (Figure 6) stakeholders expressed that CO_2 negatively affects the climate. While stakeholders can affirm that they are aware of climate change, deep understanding of its meaning and effects might by missing [18]. A crucial understanding of climate change and its effects is indispensable, as farmers who believe that climate change is human-caused are more inclined to agree that weather patterns are changing and they are more concerned about the impact on their farms [17]. When asked during the interviews if they perceived climate change, most stakeholders expressed that they have noticed changes in precipitation patterns and increasing temperatures. The majority agreed that winters are shorter and warmer, while summers are hotter. As seen in Figure 2 average temperature in the region has indeed been following an incremental trend. This was expected as there is considerable evidence highlighting that farmers' climate change perceptions are usually in line with the actual climatic data trends [11,13,14,16,19,28].

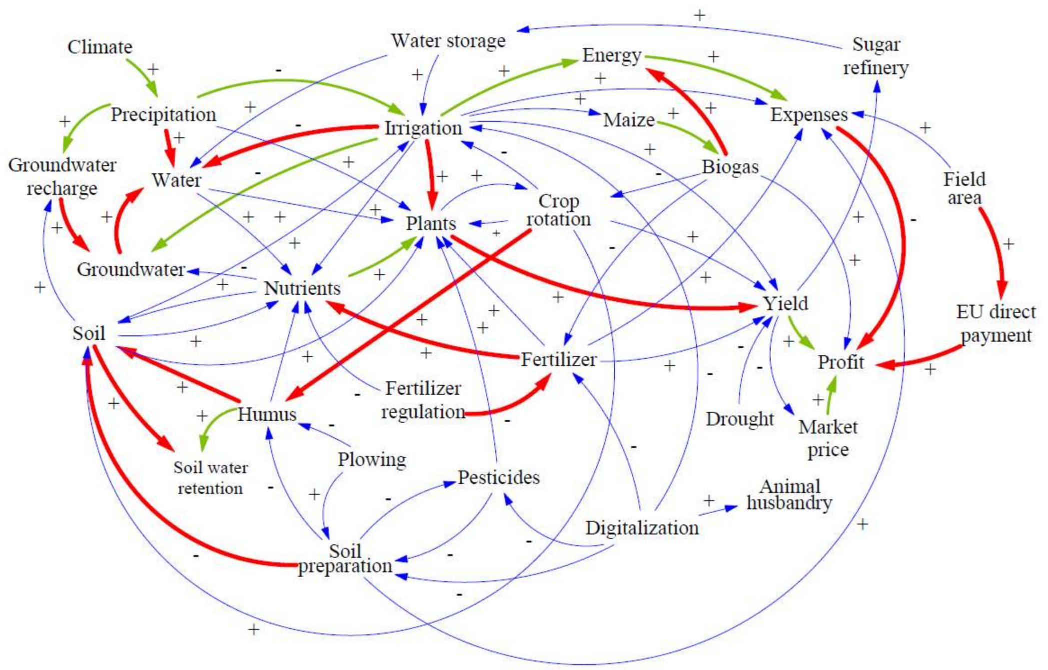

Figure 5. The preliminary model including all Tier-1 components. The thickness of the arrows represents the tier level, with low effect relationships (Tier-1) shown by thin blue arrows, considerable effect (Tier-2) by medium thick green arrows, and strong effect (Tier-3) by the thick red arrows. The binary operators represent the nature of the relationship, as they indicate if the effect is positively or negatively related to the cause.

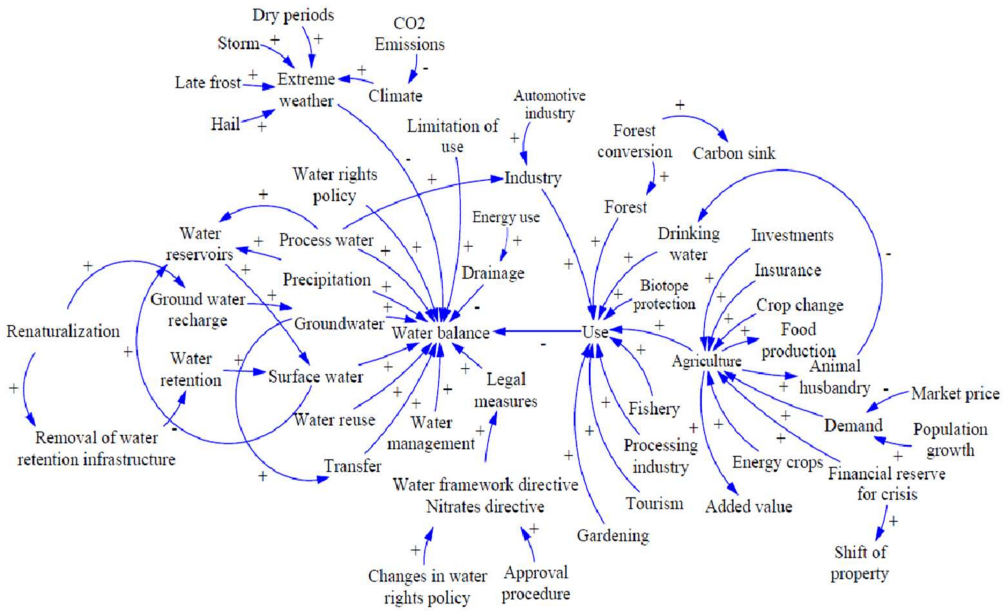

Figure 6. The group model developed during the GMB session showing in detail the water balance and the water-demanding sectors of the region. The left side of the model shows factors influencing the water balance, while the right side shows the factors and sectors influencing regional water use.

In regards to drought, in the preliminary model (Figure 5), the effect of drought on the water balance of the region and the factors leading to drought are not represented. Drought is represented as an independent event having a low effect on yields. In the group model (Figure 6), “dry periods” are part of a group of weather events affecting the water balance but they are also not linked to climate change. There is no connection between climate change and droughts in any of the models, indicating that many stakeholders see drought as a weather event that is not necessarily caused by climate change. This could be a common perspective of farmers in northern Europe, as Ibrahim and Johansson (2021) [29] found that farmers in Öland, Sweden, strongly believe that the 2018 drought was part of a natural cycle and half of them do not expect their yields to decrease. They also found out that most of the farmers were climate skeptics and that respondents had no urgency to adapt to climate change. Stakeholders can sometimes falsely believe that climate change would not affect them or that it will affect others sometime in the far future. Low risk perceptions and skepticism slows down and discourages climate change adaptation [10,11,19], while underestimating climate risk perceptions could lead to maladaptation or no adaptation at all [11,19]

Because education and access to information is the main influencing stakeholders’ perceptions on climate change [11,13–15], information should be offered to stakeholder to promote informed climate change perceptions. Climate change communication can help increase the risk awareness of stakeholders [10]. Climate change awareness can and should be influenced by information campaigns, access to information and climate change education [11,17,27]. By offering access to information and advisory services, policymakers can strengthen the adaptation capacity of rural communities [13,19,27] and improve farmers’ knowledge and capacity to support mitigation of and adaptation to climate change [11,75]. Climate messages with a negative emotional content that emphasize the threat of climate change have proven the most efficient in increasing climate change adaptation intentions and the risk perception [76].

4.2. Adaptation Measures Implemented and under Development in the Region

For our second objective, several adaptation measures were observed in the preliminary and group models and mentioned by stakeholders (Table 2). The most frequently mentioned adaptation measure was the creation of water storage infrastructure, which is present in both the preliminary and the group models (Figures 5 and 6). By storing water, which might come from water treatment plants or industry, the available water of the region could be increased. This could decrease the pressure on groundwater by reducing the need for extracting groundwater for irrigation. The local sugar refinery has already created a water reservoir to store process water, which is later used for irrigation. The water reuse project implemented by the sugar refinery demonstrates the successful incorporation of water storage projects. However, while water reservoirs for agriculture can support climate change adaptation they require high capital investment and have high social and environmental costs [77]. Besides, the scale of this particular project is currently too small to have a significant effect on the amount of available water in the region (Figure 5).

Stakeholders also continuously pointed out the importance of humus formation to promote fertile soils and increase the soil water retention capacity (Figure 5). The majority of the stakeholders are aware that the sandy soils need to be enriched with humus. The humification suggested by stakeholders is closely related to crop rotation and tillage (Figure 5) [78]. Soils with a higher percentage of organic matter are more fertile and have a better water holding capacity, which in turn increases soil moisture and reduces the demand for water (Figure 5) [79]. While stakeholders are clearly aware of this, the current crop rotation and tillage practices do not promote humus formation. It is also important to consider that humification is a process that usually takes decades to complete. There is a widespread belief that no tillage, one of the three principles of Conservation Agriculture, is only possible by using herbicides and pesticides (Figure 5) [29]. Organic farmers, however, stated that their practices promote humification and that they fully enjoyed the benefits of humus-rich soils. One organic farm had been promoting humification for two generations and claimed that they did not even have to irrigate their fields during the 2018 drought.

Table 2. Identified suggested and implemented adaptation measures and corresponding models.

Adaptation Measure	Prel. Model	Group Model	Currently Implemented	Challenge
Water storage	Yes	Yes	At a small scale	High initial investment
Humification	Yes	No	Some farmers	Extremely slow and dependent on crop rotation
Renaturalization	No	Yes	No	Possible reduction of groundwater recharge and loss of usable land
Digitalization	Yes	No	Several farmers	Initial investment
New crop rotation	Yes	No	No	Rebounding and shift in vulnerability
Financial reserve	No	Yes	No	Rebounding and shift in vulnerability
Water management	No	Yes	Yes	Cover everyone's needs
EU legal measures	No	Yes	Yes	Could create new externalities

Renaturalization was mentioned as an option to promote groundwater recharge and improve the state of surface water (Figure 6). Stakeholders mentioned that renaturalization should improve the state of superficial waters. Additionally, by promoting recharge and reducing water retention, the total available water of the region could be increased. There were, however, no major renaturalization projects in the region at the time this study took place. Extensive research should be carried out before implementing land use change projects as there are mixed results explaining the effect of woodlands on groundwater recharge. In some cases, native and exotic woodlands substantially decrease groundwater recharge, when compared to grassland, due to higher rainfall interception [80,81]. In other cases, natural forest and forest plantations have higher degree infiltration as degraded land [81,82]. However, agriculture and forest do have a higher groundwater recharge capacity when compared to urban areas [83].

Digitalization was also suggested as a way to improve the efficiency of agriculture. Digitalization is the base for precision agriculture [84]. New technology allows farmers to increase the efficiency of their irrigation, tillage, fertilizer application, herbicide application, and animal husbandry (Figure 5). Mentioned examples include GPS guided vehicles for fertilizer and pesticide application and soil humidity monitoring systems. Precision agriculture benefits farmers as it means less waste of the previously mentioned resources and, therefore, lower cost [75]. Precision farming has a high potential for mitigation as it also promotes a reduction of emissions and higher yields [75]. Farmers who engage in precision agriculture become more focused on economy but also on environmental benefits and climate change adaptation and mitigation [29]. Several farmers were already investing in new technologies, for example in GPS guided tractors or systems to continuously monitor the humidity in the soil and irrigate their fields only when needed.

Several stakeholders suggested a new crop rotation or diversification of crops as an adaptation measure because of the high water consumption of current crop rotation. Diversification of crops increases the resilience to climate change and drought [75,85,86]. The effect current crops have on water demand is represented in both the preliminary and the group model (Figures 5 and 6). While current crop rotation has a high water-demand, a stakeholder also mentioned that a large proportion of the current infrastructure is built around these crops. Farmers mentioned their reluctance to change crops because it could have a large impact on crop yields and subsequently on their profits (Figure 5). This mirrors the observation in Scandinavia by Ibrahim and Johansson (2021) [29]. While, changing crops could reduce water demand, these changes are costly and could lead to rebounding maladaptation due to the incompatibility with market demand [87]. Market demand incompatibility could also lead to maladaptation through a shift in vulnerability, as the local sugar refinery and the biogas plants, two of the strongest buyers of farmers' yields, depend on sugar beets and maize.

A financial reserve for crises was also suggested (Figure 6) as an adaptation measure to help agriculture hedge against natural hazards such as droughts, floods, and/or crop failure. There is, however, no consensus around how to create the financial reserve and who should be responsible for it. Financial reserves could benefit the region during extreme events. However, this kind of measure can also increase the farmers' dependence on government [88]. It may be problematic for stakeholders to rely exclusively on financial bailout. This measure would be available only following catastrophic weather events. There may be the danger of a "moral hazard" [89], where the prospect of a bailout incentivizes stakeholders to neglect adaptation measures. Therefore, considering this financial reserve as an excuse to abandon the implementation of other adaptation measures should be avoided. Doing this could lead to rebounding maladaptation.

Several types of water management strategies are present in the group model (Figure 6). Among them are water rights policy and limitation of use. These water management strategies, such as water usage regulation, have a direct influence on the water balance of the region. The region already has already water management bodies and a solid water usage regulation in place. The current regulation, however, was designed to manage a system with stable climate conditions, and it does not consider droughts or climate change. Traditionally, water management practices have relied on historical data. This practice does not consider the effects of climate change [90,91]. Improved water resources management should take into account the effects of climate change [39,91]. The new strategies should consider short- and long-term demand and rely on available scientific resources such as climate projections and hydrological modeling under climate change scenarios [90]. This could help improve the resilience of the region and benefit all users as competition for water resources intensifies [90]. Apart from climate change, developing successful water management practices has other challenges such as the different interests of stakeholders, the complexity of government networks, and multiple decision makers [92].

Lastly, legal measures at a European level (Figure 6), such as the European Water Framework Directive [93] and Nitrates Directives [94], were also mentioned as mechanisms for climate change adaptation and environmental protection. This perception goes in line with the intentions of the EU policy. Policies such as the EU Cap, the EU Floods Directive, the EU Adaptation Strategy and the EU Water Scarcity and Drought Strategy, are efforts to provide a framework to encourage adaptation at a farm level [75].

4.3. Possible Challenges for Adaptation in NELS

Based on the stakeholder perceptions summarized in the triangulated model (Figure 7), we have identified that NELS has three strengths but also four challenges to overcome (Table 3). The first strength is existing irrigation systems that serve as a buffer during dry periods, as exhibited in the 2018 drought. A second strength is that the region already has water usage regulations. The law has a direct effect on water balance as it controls the amount of water that can be extracted (Figures 6 and 7). However, the current water regulations do not consider either drought events or the effects of climate change. The third strength is that the physical and governmental infrastructure necessary to manage water resources and allocate water rights already exists. According to stakeholders, these government bodies are powerful and have been efficient in controlling water allocation and extraction.

The system's main vulnerability is the types of crops currently planted. Crops (Figures 5 and 7) directly affect humus formation, but the current crop rotation does not promote this process. Additionally, the current crop rotation has a direct impact on water demand (Figure 7), as it consists mainly of potatoes, sugar beets, and corn, all of which are water-demanding crops. A second challenge is that irrigation use has two drawbacks: high energy cost (Figures 5 and 7) and increased water extraction, which affects water balance and potentially other users (Figures 5–7) if no other adaptation measures are implemented.

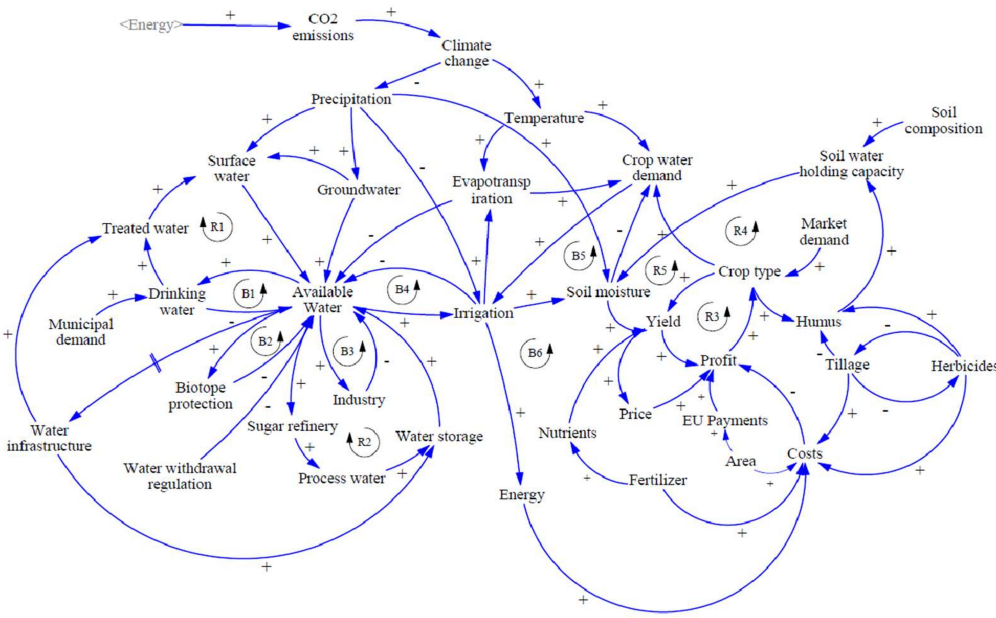

Figure 7. The triangulated model, product of triangulation and compilation of the gathered data. A "+" indicates a proportional effect and a "-" indicates an inversely proportional effect. In the model the main balancing and reinforcing feedback loops are marked; with (R) for reinforcing (or positive) and (B) for balancing (or negative) feedback loops.

Table 3. Strengths and challenges of the region in coping with possible future problems caused by climate change.

	Characteristic	Significance	Possible Consequences
Strengths	Irrigation systems	Ability to compensate for and cope with dry periods	Higher yield than rainfed agriculture
	Water usage regulation	Controlled and managed use of water resources	Conservation of water resources while covering users' needs
	Infrastructure and government bodies	Government and water management bodies already exist	Efficient and fast implementation of measures
Challenges	Irrigation systems	More water extraction More energy consumption	Increased pressure on water balance Increase in costs and reduction of profit
	Water usage regulation does not consider climate projections	Inability to cope with drought events Incremental water extraction as temperatures rise Increased extraction during drought events	Economic loss in at least one sector Cumulative pressure on water balance Drastic pressure on water balance
	Crop rotation	High water demand Not ideal for humification	Possible ever-increasing water demand under climate change
	Multiple water users	Allocating water for all users during drought events More water extraction	Water conflicts Increased pressure on water balance

As a last challenge, the region has a variety of water users with the most important being agriculture, drinking water, industry, and natural habitats (Figure 7). The variety of water users could make water management a controversial environmental policy issue, because of the diversity of interests and the increasing level of conflict among stakeholders, especially during prolonged drought periods. More users also mean higher water extraction, which according to stakeholders could lead to future water conflicts.

5. Conclusions

We implemented a Group Model Building process based on Vennix (1996) [23] with two additions to the method: (1) an aggregated preliminary model based on the individual models and; (2) a triangulation process to develop a final qualitative model. This novel approach to GMB applied in NELS allowed us to explore our three objectives. Our study showed that creating a preliminary model by merging the individual models displays the shared or common perspective of all stakeholders, and it helps distinguish between interactions with a strong or weak impact on the region's dynamics. The triangulation process showed that by comparing all the gathered information, the modeler can develop a qualitative model, which can be used to explore the strengths and challenges of the region. This model offers several advantages. First, triangulation processes encourage objectivity by comparing the stakeholders' perceptions with information from other databases, and the personal observations of the modeler. Second, triangulation helps to compile the information gathered during the research into a single model, which is easier to understand. Third, it does not limit the collection of information to one source as it allows the modeler to include information gathered from other data sources.

Our results suggest that stakeholders are aware of climate change but they lack a deep understanding of the effects that climate change might have on the region and its relation to drought events. Stakeholders are aware of adaptation measures they could implement to cope with these challenges. However, we conclude that NELS is currently unprepared to cope with the effects of climate change. The unpreparedness of NELS lies mainly in the fact that the majority of the adaptation measures suggested by the stakeholders imply large-scale system changes, which require high initial investments or imply an additional risk. Because of this, no major adaptation efforts have been made at either a farm level or regional level. To promote more accurate climate change perceptions and thus trigger adaptation, we propose climate change communication as a solution to underestimate climate risk perceptions. In regards to adaptation measures, we propose large economic incentives as the majority of the suggested adaptation measures require significant initial investments, which farmers are not able to pay for themselves.

Finally, we recommend a better management of water resources taking into account the effects of climate change. This could help improve the resilience of the region and benefit all users as competition for water resources intensifies. Developing successful water management practices has other challenges, including the different interests of stakeholders, the complexity of government networks, and multiple decision makers. Despite the challenges and difficulties, developing a better water management strategy presents an opportunity to initiate the adaptation process without great economic investment. The region could also benefit from the development of a drought management plan. By implementing such a plan, water managers could enforce restrictions and controls to ensure water is available for all actors during drought periods and, at the same time, avoid overexploitation of water resources. This solution is extremely challenging, as it requires a deep analysis of available water resources, a risk analysis process, and changes to the current law. Encouragingly, the NELS region is supported by sound infrastructure and effective governing bodies, which makes tackling this challenge possible.

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References

1. Cruz, G.; Gravina, V.; Baethgen, W.E.; Taddei, R. A Typology of Climate Information Users for Adaptation to Agricultural Droughts in Uruguay. *Clim. Serv.* **2021**, *22*, 100214. [CrossRef]
2. Stein, U.; Özerol, G.; Tröltzsch, J.; Landgrebe, R.; Szendrenyi, A.; Vidaurre, R. European Drought and Water Scarcity Policies. In *Governance for Drought Resilience*; Bressers, H., Bressers, N., Larrue, C., Eds.; Springer: Cham, Switzerland, 2016; pp. 17–44. ISBN 9783319296715.
3. Ionita, M. On the Curious Case of the Recent Decade, Mid-Spring Precipitation Deficit in Central Europe. *npj Clim. Atmos. Sci.* **2020**, 1–10. [CrossRef]
4. Leitner, M.; Babcicky, P.; Schinko, T.; Glas, N. The Status of Climate Risk Management in Austria. Assessing the Governance Landscape and Proposing Ways Forward for Comprehensively Managing Flood and Drought Risk. *Clim. Risk Manag.* **2020**, *30*, 100246. [CrossRef]
5. Samaniego, L.; Thober, S.; Kumar, R.; Wanders, N.; Rakovec, O.; Pan, M.; Zink, M.; Sheffield, J.; Wood, E.F.; Marx, A. Anthropogenic Warming Exacerbates European Soil Moisture Droughts. *Nat. Clim. Chang.* **2018**, *8*, 421–426. [CrossRef]
6. Intergovernmental Panel on Climate Change. *Global Warming of 1.5 °C, an IPCC Special Report on the Impacts of Global of 1.5 °C above Pre-Industrial Levels*; Intergovernmental Panel on Climate Change: Incheon, Korea, 2018.
7. Naumann, G.; Cammalleri, C.; Mentaschi, L.; Feyen, L. Increased Economic Drought Impacts in Europe with Anthropogenic Warming. *Nat. Clim. Chang.* **2019**. [CrossRef]
8. European Environment Agency. *Climate Change, Impacts and Vulnerability in Europe 2012*; European Environment Agency: Copenhagen, Denmark, 2012.
9. Thober, S.; Marx, A.; Boeing, F. *Auswirkungen Der Globalen Erwärmung Auf Hydrologische Und Agrarische Dürren Und Hochwasser in Deutschland*; Helmholtz Centre for Environmental Research—UFZ: Leipzig, Germany, 2018.
10. Maltby, K.M.; Simpson, S.D.; Turner, R.A. Scepticism and Perceived Self-Efficacy Influence Fishers' Low Risk Perceptions of Climate Change. *Clim. Risk Manag.* **2021**, *31*, 100267. [CrossRef]
11. Abid, M.; Scheffran, J.; Schneider, U.A.; Elahi, E. Farmer Perceptions of Climate Change, Observed Trends and Adaptation of Agriculture in Pakistan. *Environ. Manag.* **2019**, 110–123. [CrossRef]
12. Aidoo, D.C.; Boateng, S.D.; Freeman, C.K.; Anaglo, J.N. The Effect of Smallholder Maize Farmers' Perceptions of Climate Change on Their Adaptation Strategies: The Case of Two Agro-Ecological Zones in Ghana. *Heliyon* **2021**, *7*, e08307. [CrossRef]
13. Jha, C.K.; Gupta, V. Farmer' s Perception and Factors Determining the Adaptation Decisions to Cope with Climate Change: An Evidence from Rural India. *Environ. Sustain. Indic.* **2021**, *10*, 100112. [CrossRef]
14. Nyang'au, J.O.; Mohamed, J.H.; Mango, N.; Makate, C.; Wangeci, A.N. Smallholder Farmers' Perception of Climate Change and Adoption of Climate Smart Agriculture Practices in Masaba South Sub-County, Kisii, Kenya. *Heliyon* **2021**, *7*, e06789. [CrossRef]
15. Li, W.; Yuan, K.; Yue, M.; Zhang, L.; Huang, F. Climate Change Risk Perceptions, Facilitating Conditions and Health Risk Management Intentions: Evidence from Farmers in Rural China. *Clim. Risk Manag.* **2021**, *32*, 100283. [CrossRef]
16. Snaibi, W.; Mezrhab, A.; Sy, O.; Morton, J.F. Perception and Adaptation of Pastoralists to Climate Variability and Change in Morocco' s Arid Rangelands. *Heliyon* **2021**, *7*, e08434. [CrossRef] [PubMed]
17. Mase, A.S.; Gramig, B.M.; Prokopy, L.S. Climate Change Beliefs, Risk Perceptions, and Adaptation Behavior among Midwestern US Crop Farmers. *Clim. Risk Manag.* **2017**, *15*, 8–17. [CrossRef]
18. Hundera, H.; Mpandeli, S.; Bantider, A. Smallholder Farmers' Awareness and Perceptions of Climate Change in Adama District, Central Rift Valley of Ethiopia. *Weather Clim. Extrem.* **2019**, *26*, 100230. [CrossRef]
19. Mahmood, N.; Arshad, M.; Mehmood, Y.; Faisal, M.; Harald, K. Farmers' Perceptions and Role of Institutional Arrangements in Climate Change Adaptation: Insights from Rainfed Pakistan. *Clim. Risk Manag.* **2021**, *32*. [CrossRef]
20. Phan, T.D.; Bertone, E.; Pham, T.D.; Pham, T. V Perceptions and Willingness to Pay for Water Management on a Highly Developed Tourism Island under Climate Change: A Bayesian Network Approach. *Environ. Chall.* **2021**, *5*, 100333. [CrossRef]
21. Kotir, J.H.; Smith, C.; Brown, G.; Marshall, N.; Johnstone, R. A System Dynamics Simulation Model for Sustainable Water Resources Management and Agricultural Development in the Volta River Basin, Ghana. *Sci. Total Environ.* **2016**, *573*, 444–457. [CrossRef]
22. Williams, D.S. Enhancing Autonomy for Climate Change Adaptation Using Participatory Modeling. *Weather Clim. Soc.* **2020**, *12*, 667–678. [CrossRef]

23. Vennix, J.A.M. *Group Model Building: Facilitating Team Learning Using System Dynamics*; John Wiley & Sons Ltd: Hoboken, NJ, USA, 1996; ISBN 0-471-95355-5.
24. Purwanto, A.; Susnik, J.; Suryadi, F.X.; de Fraiture, C. Using Group Model Building to Develop a Causal Loop Mapping of the Water-Energy-Food Security Nexus in Karawang Regency, Indonesia. *J. Clean. Prod.* **2019**, *240*, 118170. [CrossRef]
25. Voinov, A. Participatory Modeling for Sustainability. In *Encyclopedia of Sustainable Technologies*; Elsevier: Amsterdam, The Netherlands, 2017; pp. 33–39.
26. Akkermans, H. *Modelling with Managers: Participative Business Modelling for Effective Strategic Decision-Making*; Technische Universiteit Eindhoven: Eindhoven, The Netherlands, 1995.
27. Asare-Nuamah, P.; Botchway, E. Heliyon Comparing Smallholder Farmers' Climate Change Perception with Climate Data: The Case of Adansi North District of Ghana. *Heliyon* **2019**, *5*, e03065. [CrossRef]
28. Elum, Z.A.; Modise, D.M.; Marr, A. Farmer' s Perception of Climate Change and Responsive Strategies in Three Selected Provinces of South Africa. *Clim. Risk Manag.* **2017**, *16*, 246–257. [CrossRef]
29. Ibrahim, M.A.; Johansson, M. Attitudes to Climate Change Adaptation in Agriculture—A Case Study of Öland, Sweden. *J. Rural Stud.* **2021**. [CrossRef]
30. Umweltbundesamt Struktur Der Flächennutzung. Available online: https://www.umweltbundesamt.de/daten/flaeche-boden-land-oekosysteme/flaeche/struktur-der-flaechennutzung#textpart-2 (accessed on 23 October 2019).
31. Grocholl, J. *Effiziente Wassernutzung Im Ackerbau Nord-Ost-Niedersachsens: Möglichkeiten Zur Anpassung an Den Prognostizierten Klimawandel*; Lower Saxony Chamber of Agriculture, Uelzen District office: Uelzen, Germany, 2011.
32. Jensen, K.; Knieling, J.; Rechid, D. Charakteristika Der Metropolregion Hamburg. In *Kursbuch: Klimaanpassung*; TuTech publisher: Hamburg, Germany, 2014; pp. 4–7.
33. LWK Niedersachsen. *No Regret—Genug Wasser Für Die Landwirtschaft?! Projektbericht—Kurzfassung*; Lower Saxony Chamber of Agriculture, Uelzen district office: Uelzen, Germany, 2008.
34. Wittenberg, H. Groundwater Abstraction for Irrigation and Its Impacts on Low Flows in a Watershed in Northwest Germany. *Resources* **2015**, *4*, 566–576. [CrossRef]
35. Ostermann, U. Wasserhaushalt in Nordostniedersachsen Durch Wassernutzung Und—Management Ausgleichen. *Wasser und Abfall* **2019**, *21*, 39–46. [CrossRef]
36. Egerer, S.; Valencia-Cotera, R.; Celliers, L.; Máñez Costa, M. A Leverage Points Analysis of a Qualitative System Dynamics Model for Climate Change Adaptation in Agriculture. *Agric. Syst.* **2021**, *189*. [CrossRef]
37. Niedersächsisches Ministerium für Umwelt Energie und Klimaschutz. *Empfehlung Für Eine Niedersächsische Strategie Zur Anpassung an Die Folgen Des Klimawandels*; Niedersächsisches Ministerium für Umwelt Energie und Klimaschutz: Hannover, Germany, 2012.
38. Rechid, D.; Petersen, J.; Jacob, D. Klimaprojektionen Für Die Metropolregion Hamburg. In *Kursbuch: Klimaanpassung*; TuTech Verlag: Hamburg, Germany, 2014; pp. 8–11.
39. Scheihing, K.W. Klimawandel in Niedersachsen Und Mögliche Folgen Für Die Grundwasserbewirtschaftung: Ein Review. *Hydrol. und Wasserbewirtschaft* **2019**. [CrossRef]
40. Bender, S.; Butts, M.; Hagemann, S.; Smith, M.; Vereecken, H.; Wendland, F. *Der Einfluss Des Klimawandels Auf Die Terrestrischen Wassersysteme in Deutschland*; Climate Service Center Germany: Hamburg, Germany, 2017.
41. Trömel, S.; Schönwiese, C.D. Robust Trend Estimation of Observed German Precipitation. *Theor. Appl. Climatol.* **2008**, *93*, 107–115. [CrossRef]
42. Cornes, R.C.; Van Der Schrier, G.; Jones, P.D.; Besselaar, E.J.M. Van Den An Ensemble Version of the E-OBS Temperature and Precipitation Data Sets. *J. Geophys. Res. Atmos.* **2018**, 9391–9409. [CrossRef]
43. Sun, J.; Yang, K. The Wicked Problem of Climate Change: A New Approach Based on Social Mess and Fragmentation. *Sustainability* **2016**, *8*, 1312. [CrossRef]
44. Termeer, C.; Dewulf, A.; Breeman, G. Governance of Wicked Climate Adaptation Problems. In *Climate Change Management*; Springer: Berlin/Heidelberg, Germany, 2013; pp. 27–39.
45. Webber, M.M. Dilemmas in a General Theory of Planning. *Policy Sci.* **1973**, *4*, 155–169.
46. Elia, G.; Margherita, A. Can We Solve Wicked Problems? A Conceptual Framework and a Collective Intelligence System to Support Problem Analysis and Solution Design for Complex Social Issues. *Technol. Forecast. Soc. Chang.* **2018**, *133*, 279–286. [CrossRef]
47. Tietjen, A.; Jørgensen, G. Landscape and Urban Planning Translating a Wicked Problem: A Strategic Planning Approach to Rural Shrinkage in Denmark. *Landsc. Urban Plan.* **2016**, *154*, 29–43. [CrossRef]
48. Eden, C. Cognitive Mapping. *Eur. J. Oper. Res.* **1988**, *36*, 1–13. [CrossRef]
49. Sterman, J.D. *Bussiness Dynamics. Systems Thinking and Modeling for a Complex World*; Shelstad, J.J., Ed.; McGraw-Hill Higher Education: New York, NY, USA, 2000; ISBN 007238915X.
50. Forrester, J.W. Policies, Decisions and Information Sources for Modeling. *Eur. J. Oper. Res.* **1992**, *59*, 42–63. [CrossRef]
51. Carmona Costa, M. *Risk Perception and Governance Performance in Multi-Sector Partnerships. The Case Study of the Permanent Drought Commission of the Jucar River*; Universität Hamburg: Hamburg, Germany, 2016.
52. Rouwette, E.; Bleijenbergh, I.; Vennix, J. Group Model-Building to Support Public Policy: Addressing a Conflictcted Situation in a Problem Neighbourhood. *Syst. Res. Behav. Sci.* **2016**, *78*, 64–78. [CrossRef]
53. Black, L.J. When Visuals Are Boundary Objects in System Dynamics Work. *Syst. Dyn. Rev.* **2013**, *29*, 70–86. [CrossRef]

54. Rich, K.M.; Rich, M.; Dizyee, K. Participatory Systems Approaches for Urban and Peri-Urban Agriculture Planning: The Role of System Dynamics and Spatial Group Model Building. *AGSY* **2016**. [CrossRef]
55. Zagonel, A.A. Model Conceptualization in Group Model Building: A Review of the Literature Exploring the Tension between Representing Reality and Negotiating a Social Order. In Proceedings of the 2002 International Conference of the System Dynamics Society, Palermo, Italy, 28 July–1 August 2002; pp. 1–68.
56. Hovmand, P.S. Group Model Building Approaches to Group Model Building. In *Community Based System Dynamics*; Springer: New York, NY, USA, 2013; pp. 17–30.
57. Berard, C. Group Model Building Using System Dynamics: An Analysis of Methodological Frameworks. *Electron. J. Bus. Res. Methods* **2010**, *8*, 35–45.
58. Stave, K. Participatory System Dynamics Modeling for Sustainable Environmental Management: Observations from Four Cases. *Sustainability* **2010**, *2*, 2762–2784. [CrossRef]
59. Máñez, M.; Osorio, J.; Kovalevsky, D. *WP-13 Deliverable D13.1 Generic Integrative Modeling Approach Guideline*; Climate Service Center Germany: Hamburg, Germany, 2017.
60. Vugteveen, P.; Rouwette, E.; Stouten, H.; Van Katwijk, M.M.; Hanssen, L. Developing Social-Ecological System Indicators Using Group Model Building. *Ocean Costal Manag.* **2015**, *109*, 29–39. [CrossRef]
61. Chen, H.; Chang, Y.; Chen, K. Integrated Wetland Management: An Analysis with Group Model Building Based on System Dynamics Model. *J. Environ. Manag.* **2014**, *146*, 309–319. [CrossRef]
62. Reed, M.S.; Graves, A.; Dandy, N.; Posthumus, H.; Hubacek, K.; Morris, J.; Prell, C.; Quinn, C.H.; Stringer, L.C. Who's in and Why? A Typology of Stakeholder Analysis Methods for Natural Resource Management. *J. Environ. Manag.* **2009**, *90*, 1933–1949. [CrossRef] [PubMed]
63. Sterman, J.D. All Models Are Wrong: Reflections on Becoming a Systems Scientist. *Syst. Dyn. Rev.* **2002**, *18*, 501–531. [CrossRef]
64. Al-samarraie, H.; Hurmuzan, S. A Review of Brainstorming Techniques in Higher Education. *Think. Ski. Creat.* **2017**. [CrossRef]
65. Pattison, P.E.; Robins, G.L.; Snijders, T.A.B.; Wang, P. Conditional Estimation of Exponential Random Graph Models from Snowball Sampling Designs. *J. Math. Psychol.* **2013**, *57*, 284–296. [CrossRef]
66. Malek, Ž. Fuzzy-Logic Cognitive Mapping: Introduction and Overview of the Method. In *Environmental Modeling with Stakeholders*; Springer International Publishing: Cham, Switzerland, 2017; pp. 127–143.
67. Richardson, G.P.; Andersen, D.F. Teamwork in Group Model Building. *Syst. Dyn. Rev.* **1995**, *11*, 113–137. [CrossRef]
68. Star, S.L.; Grisemer, J.R. Institutional Ecology, "translations" and Boundary Objects: Amateurs and Professionals in Berkley's Museum of Vertebrate Zoology, 1907–1936. *Soc. Stud. Sci.* **1989**, *19*, 387–420. [CrossRef]
69. Black, L.J.; Andersen, D.F. Using Visual Representations as Boundary Objects to Resolve Conflict in Collaborative Model-Building Applications. *Syst. Res. Behav. Sci.* **2012**, *29*, 194–208. [CrossRef]
70. Denzin, N.K. *The Research Act: A Theoretical Introduction to Sociological Methods*; Routledge: London, UK, 2009; ISBN 9780202362489.
71. Bryman, A. *Social Research Methods*, 4th ed.; Oxford University Press: Oxford, UK, 2012; ISBN 978–0–19–958805–3.
72. Kaivo-oja, J. Towards Better Participatory Processes in Technology Foresight: How to Link Participatory Foresight Research to the Methodological Machinery of Qualitative Research and Phenomenology? *Futures* **2017**, *86*, 94–106. [CrossRef]
73. Tischer, D. Collecting Network Data from Documents to Reach Non-Participatory Populations. *Soc. Netw.* **2020**. [CrossRef]
74. Hassanzadeh, E.; Elshorbagy, A.; Wheater, H.; Gober, P. Managing Water in Complex Systems: An Integrated Water Resources Model for Saskatchewan, Canada. *Environ. Model. Softw.* **2014**, *58*, 12–26. [CrossRef]
75. European Environment Agency. *Climate Change Adaptation in the Agriculture Sector in Europe*; European Environment Agency: Copenhagen, Denmark, 2019.
76. Brosch, T. ScienceDirect Affect and Emotions as Drivers of Climate Change Perception and Action: A Review. *COBEHA* **2021**, *42*, 15–21. [CrossRef]
77. International Water Management Institute. *Water Policy Brief*; International Water Management Institute: Colombo, Sri Lanka, 2009.
78. Marcinkeviciene, A.; Boguzas, V.; Balnyte, S.; Pupaliene, R.; Velicka, R. Influence of Crop Rotation, Intermediate Crops, and Organic Fertilizers on the Soil Enzymatic Activity and Humus Content in Organic Farming Systems. *Eurasian Soil Sci.* **2013**, *46*, 198–203. [CrossRef]
79. Drastig, K.; Prochnow, A.; Libra, J.; Koch, H.; Rolinski, S. Irrigation Water Demand of Selected Agricultural Crops in Germany between 1902 and 2010. *Sci. Total Environ.* **2016**, *569–570*, 1299–1314. [CrossRef] [PubMed]
80. Fan, J.; Oestergaard, K.T.; Guyot, A.; Lockington, D.A. Estimating Groundwater Recharge and Evapotranspiration from Water Table Fluctuations under Three Vegetation Covers in a Coastal Sandy Aquifer of Subtropical Australia. *J. Hydrol.* **2014**, *519*, 1120–1129. [CrossRef]
81. Ouyang, Y.; Jin, W.; Grace, J.M.; Obalum, S.E.; Zipperer, W.C.; Huang, X. Journal of Hydrology: Regional Studies Estimating Impact of Forest Land on Groundwater Recharge in a Humid Subtropical Watershed of the Lower Mississippi River Alluvial Valley. *J. Hydrol. Reg. Stud.* **2019**, *26*, 100631. [CrossRef]
82. Krishnaswamy, J.; Bonell, M.; Venkatesh, B.; Purandara, B.K.; Rakesh, K.N.; Lele, S.; Kiran, M.C.; Reddy, V.; Badiger, S. The Groundwater Recharge Response and Hydrologic Services of Tropical Humid Forest Ecosystems to Use and Reforestation: Support for the 'Infiltration-Evapotranspiration Trade-off Hypothesis'. *J. Hydrol.* **2013**, *498*, 191–209. [CrossRef]

83. Lamichhane, S.; Shakya, N.M. Journal of Hydrology: Regional Studies Alteration of Groundwater Recharge Areas Due to Land Use/Cover Change in Kathmandu Valley, Nepal. *J. Hydrol. Reg. Stud.* **2020**, *26*, 100635. [CrossRef]
84. European Commission. *A European Strategic Long-Term Vision for a Prosperous, Modern, Competitive and Climate Neutral Economy*; European Commission: Brussels, Belgium, 2018.
85. Intergovernmental Panel on Climate Change. *Climate Change and Land*; Intergovernmental Panel on Climate Change: Incheon, Korea, 2019.
86. Shikuku, K.M.; Winowiecki, L.; Twyman, J.; Eitzinger, A.; Perez, J.G.; Mwongera, C.; Läderach, P. Climate Risk Management Smallholder Farmers' Attitudes and Determinants of Adaptation to Climate Risks in East Africa. *Clim. Risk Manag.* **2017**, *16*, 234–245. [CrossRef]
87. Schipper, E.L.F. Primer Maladaptation: When Adaptation to Climate Change Goes Very Wrong. *One Earth* **2020**, *3*, 409–414. [CrossRef]
88. Rakgwale, T.J.; Oguttu, J.W. International Journal of Disaster Risk Reduction the Impact of the 2014–2016 Drought in Greater Letaba Local Municipality: How the Farmers Coped and Factors That Were Significantly Associated with Loss of Animals. *Int. J. Disaster Risk Reduct.* **2020**, *50*, 101869. [CrossRef]
89. Holmström, B. Moral Hazard and Observability. *Bell J. Econ.* **1979**, *10*, 74–91. [CrossRef]
90. Ludwig, F.; Van Slobbe, E.; Cofino, W. Climate Change Adaptation and Integrated Water Resource Management in the Water Sector. *J. Hydrol.* **2014**, *518*, 235–242. [CrossRef]
91. Werner, K.; Svedin, L. Climate Risk Management States, Water, and Climate: Who's Planning for Change? *Clim. Risk Manag.* **2017**, *16*, 59–72. [CrossRef]
92. Pluchinotta, I.; Pagano, A.; Tsoukiàs, A. A System Dynamics Model for Supporting Decision-Makers in Irrigation Water Management. *J. Environ. Manag.* **2018**, *223*, 815–824. [CrossRef]
93. European Commission. *Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 Establishing a Framework for Community Action in the Field of Water Policy*; European Commission: Brussels, Belgium, 2000; Volume L327.
94. European Commission. *Council Directive Concering the Protection of Waters against Pollution Caused by Nitrates from Agricultural Sources (91/676/EEC)*; European Commission: Brussels, Belgium, 1991.

CHAPTER 3: *An Assessment of Climate Change Adaptation Measures for Agriculture in Seewinkel*

An assessment of water management measures for climate change adaptation of agriculture in Seewinkel

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Climate change adaptation, system dynamics, agriculture, Seewinkel, water resources

ABSTRACT

Climate change is expected to increase the frequency, intensity, and duration of droughts. During the last decades, Europe has experienced a series of heatwaves and droughts. Countries in Central Europe, which were originally considered water rich, are now experiencing precipitation deficits, which affect agricultural productivity. Evidence of the effectiveness of adaptation measures is therefore critical to develop appropriate climate change adaptation plans and ensure food security. The semi-arid region of Seewinkel in Austria was taken as a case study due to its extensive agricultural industry and its unique biosphere of saline lakes (IUCN category II classified area). Adaptation measures discussed and suggested by local stakeholders were analyzed to determine their efficacy under different climate change scenarios. These measures include changing crops, increasing irrigation efficiency and artificially recharging the local aquifer. A System Dynamics Model (SD) was developed for Seewinkel to serve as a tool for water policy analysis. The model considers the interactions between the local aquifer, water extractions by agriculture, and water flows to the saline lakes. The model was calibrated using local historical observational data and forced with bias-adjusted climate data (EURO-CORDEX) for three representative concentration pathways (RCP)s (2010 – 2100). Our results show that a combination of measures will be the most effective to both, maintain local agriculture production and local water resources under all climate change scenarios, followed by changing crops, increasing irrigation efficiency and lastly artificial aquifer recharge.

3.1. INTRODUCTION

The agricultural sector is the biggest freshwater consumer as it accounts for 70% of water withdrawals globally (FAO, 2018; IPCC, 2019). Irrigated areas represent 20% of the cropland and 40%

of the global food production (Mcdermid et al., 2021; Scanlon et al., 2012). Since the 1960s, irrigation water volume has doubled worldwide (IPCC, 2019). On global scale, groundwater has declined due to the intensification of groundwater-fed irrigation since the beginning of the 21st century (IPCC, 2022). In dry regions agricultural groundwater extraction has caused groundwater depletion and influenced the water cycle at local and regional scales (Dalin et al., 2017; Gleeson et al., 2012; IPCC, 2021; Scanlon et al., 2012). As a result, in semi-arid regions, water scarcity is now one of the main problems to be solved (Correia de Araujo et al., 2019).

In the European Union (EU), agriculture covers approximately 40% of the land (EEA, 2019) and it accounts for 24% of the water extractions (EEA, 2021). In some regions of the EU, the total irrigated area has doubled but at EU level irrigation demand has been reduced by 28% since 1990 (EEA, 2021). European agriculture extracts 37% of its water from rivers, 36% from groundwater bodies and 27% from reservoirs (EEA, 2021). It is also the largest net water user, consuming 40 – 60% of the European net water use (EEA, 2021). Groundwater extraction for agriculture has already contributed to increasing the pressure on aquifers. In the EU, Cyprus, Hungary, Spain, Greece, Malta, Italy and France have the highest proportion of groundwater bodies affected by agricultural water extractions (EEA, 2021).

In addition to this, drought has become a new problem in Central Europe. Historically, these countries were considered water-rich. However, they have experienced prolonged droughts and heatwaves since the beginning of the 21st century (Ionita, 2020; Stein et al., 2016). These drought events have caused massive losses in the agricultural sector. Current losses in Europe are estimated at €9 billion per year (Naumann et al., 2019). In the case of Austria, agricultural losses caused by drought averaged €123 million per year (2019), a figure higher than the combined agricultural losses from hail, frost, storms, and floods (Leitner et al., 2020).

On a global scale, there is high confidence that climate change will increase the frequency of concurrent droughts and heat waves (IPCC, 2021). This situation is particularly alarming for the agricultural sector as 82% of all damage caused by droughts is absorbed by agriculture (FAO, 2021). In Europe, this figure lies between 39–60% (Cammalleri et al., 2020). Climate change is expected to further alter the water balance in Europe and thus drought damage could further increase (Naumann et al., 2019; Samaniego et al., 2018). Moreover, in Europe, the effect of increasing drought events on agriculture has already become noticeable. For example, it is estimated that cereal losses increase 3 %/year because of drought (Brás et al., 2021) and that climate change will reduce wheat production by 6% for each degree Celsius of temperature increase (Asseng et al., 2015).

Because climate change is turning water management for agriculture into a more complex task, the situation will have to be addressed with adaptation (Iglesias & Garrote, 2015). Adaptation is especially important for agriculture to ensure food security (EEA, 2019) but it also has additional benefits as it strengthens the preservation of water resources (Turral et al., 2011) and promotes soil conservation (EEA, 2019). One method to promote adaptation is by water demand management (WDM). WDM refers to the measures implemented to reduce the amount of water needed to achieve a goal (Wang et al., 2016).

Climate change adaptation through water management involves the evaluation of adaptation measures using top-down impact modelling approaches (Ludwig et al., 2014; Montanari et al., 2013). Developing efficient adaptation strategies however, requires integration of water management, hydrology, and agronomy (Turral et al., 2011). Because water management decisions are usually affected by large uncertainties, climate adaptation studies should include several climate change scenarios but also use several impact models to produce robust results (Huang et al., 2018). Climate change adaptation through agricultural water management can be enhanced by understanding the risks and advantages of the proposed adaptation measures (Iglesias & Garrote, 2015).

Because the water sector is so important for other sectors, management policies have to be aware of the potential widespread impacts (Iglesias & Garrote, 2015). However, a common gap in water management is the inadequate understanding of causal relationships in the system (Strosser et al., 2012). Additionally, water management has traditionally been based on historical data with the assumption that hydrological systems were stationary but, due to climate change, this approach is no longer viable (Ludwig et al., 2014). This means that water managers should shift to include the climate scenarios in their planning. Because of this, models, which include the interactions between sectors and simulate the behavior of the system under climate change conditions, could be particularly useful for water management.

Scientific interest for Seewinkel is largely due to the region's semi-arid status and the importance of local agriculture and its water consumption patterns. Previous studies have analyzed the historical trends in the aquifer water table (Magyar et al., 2021) and the water balance of the lake Neusiedl (Soja et al., 2013) and two studies have used integrated modelling framework to analyze the effects of implementing water pricing as an adaptation measure (Karner et al., 2019; Mitter & Schmid, 2021a). However, while the last two studies have yield beneficial results for adaptation, they are limited to a 31 year horizon (2010-2040) and do not rely on climate change model ensembles for their future projections. To our knowledge, no previous study has implemented a modelling approach that considers the causal relationships between agriculture, the aquifer and the saline lakes to evaluate the long-term effect of climate change adaptation measures. Our study aims to fill this research gap.

Under this scope, this study presents an analysis of the Seewinkel region in Austria. In Seewinkel, agriculture relies on groundwater for irrigation and it shares the land with a complex system of saline lakes. This study explores the interactions between the local aquifer, the saline lakes ecosystem and agriculture, taking into account the effects of climate change on the system. We include the causal relationships in our analysis and we consider a system with changing conditions. By doing this, we wish to avoid the two common oversights mentioned above. Local stakeholders have discussed several measures to adapt to climate change. The analysis aims to determine the effectiveness of the suggested adaptation measures to: (I) adapt agriculture to climate change by reducing its water demand (II) preserve groundwater and the saline lakes ecosystem. By setting these objectives, we aim to show evidence of the effectiveness of adaptation measures to support decision makers.

For the analysis, we have developed an original System Dynamics (SD) model and calibrated it using local observational data of the aquifer, the lakes and precipitation. The SD model presented in this study simulates the interactions between agriculture, the local aquifer, the saline lakes and the climate. The SD model runs with future climate projections provided by the World Climate Research program EURO-CORDEX initiative (Jacob et al., 2014) for three climate change scenarios (RCP 2.6, 4.5, and 8.5). With the model, we compare a scenario where no adaptation is implemented (business as usual scenario) to three adaptation scenarios. The adaptation measures are based on measures suggested by stakeholders and the local government and recorded by Kropf et al. (2021) (Kropf et al., 2021). The goal of this study is to support evidence-based decision-making in the Seewinkel region by reducing the uncertainty about the efficacy of adaptation measures. By researching climate change adaptation, we also sought to encourage the conservation of local water resources and promote food security.

3.2. MATERIALS AND METHODS

3.2.1 Case study

Seewinkel is a semi-arid region (Mitter & Schmid, 2021a) located in the east of Austria in the state of Burgenland between the Lake Neusiedl and the Austrian-Hungarian border (Figure 3.1). The region is approximately 450 km^2, has an average annual temperature of 10 °C and average annual precipitation of 600 mm (Kropf et al., 2021). The region is located west of Lake Neusiedl, the largest endorheic lake in Central Europe (Kropf et al., 2021) and also the largest lake in Austria (Soja et al., 2013). A vast majority of the land in Seewinkel is used for agriculture, 56% for cropland, 6% for grassland, and 10% for vineyards (Karner et al., 2019). Because of its semi-arid conditions, local agriculture relies on irrigation. Farmers extract water from the single local aquifer, irrigate using sprinkler systems for the crops, and drip irrigation for the vineyards. Local crop production includes sugar beets, potatoes, corn, cereals, soya, and sunflower (Mitter & Schmid, 2021b). While currently water demand is dominated by agriculture, demand by other sectors such as tourism and nature conservation are increasing (Mitter & Schmid, 2021b).

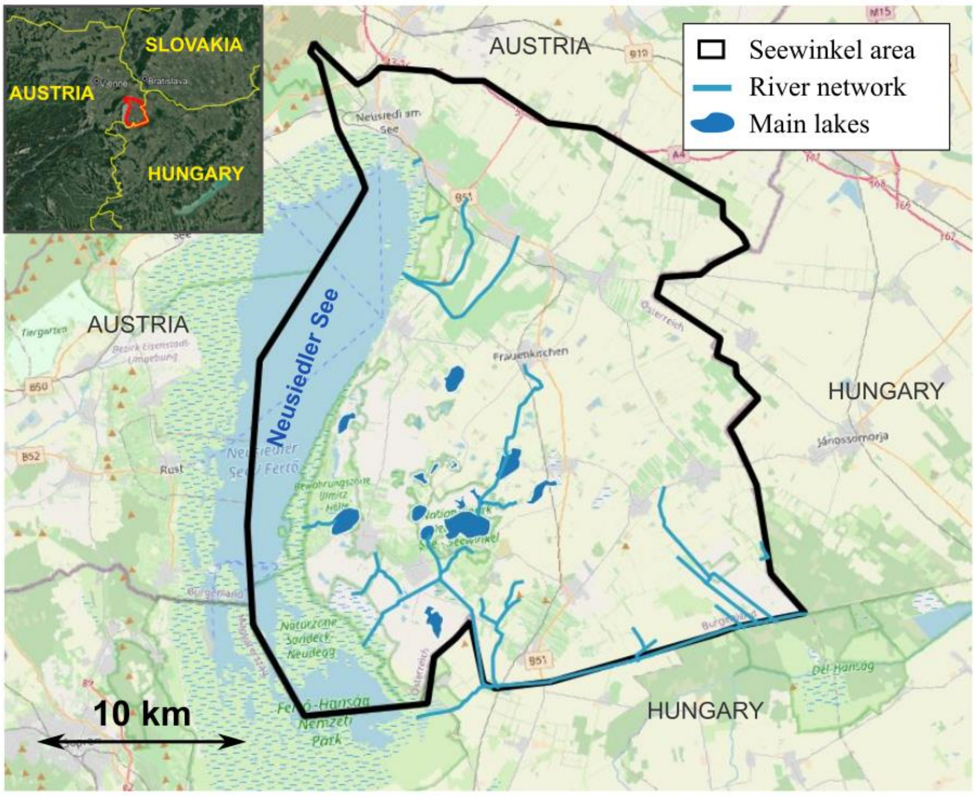

Figure 3.1. Seewinkel is located east of the Lake Neusiedl and west of the Austrian-Hungarian border. The largest saline lakes and canals are indicated in the map.

Local agriculture shares the land with numerous saline lakes called "Salzlacken". These saline lakes are a local habitat for amphibians, birds, and florae (Krachler et al., 2012; Rechnungshof Österreich, 2020). Preserving the saline lakes is of vital importance for the local biodiversity and tourism. The saline lakes are a fragile ecosystem that depends on groundwater (Magyar et al., 2021). Sinking groundwater levels could destroy these ecosystems, as a minimum groundwater level is necessary to maintain their hydro-chemical balance (Krachler et al., 2012). However, since the beginning of the 20th century, some of the lakes have been heavily modified and intentionally dried out. Maps from the middle of the 19th century show at least 139 saline lakes, 80 of them have been damaged beyond repair, leaving only 59 existing or worth considering for renaturalization (Krachler et al., 2012). The salt lakes area reduced from 3,600 ha in 1858 to only 660 ha in 2006, which implies a loss of almost 82% of this unique natural habitat (Rechnungshof Österreich, 2020).

Because Seewinkel is a semi-arid region, climate change in combination with human activities increase the risk of water stress (Magyar et al., 2021). Currently, groundwater extraction is regulated by water cooperatives (Magyar et al., 2021; Mitter & Schmid, 2021b) but the aquifer is being exploited at 78% of its sustainable yield (Bundesministerium für Landwirtschaft Regionen und Tourismus, 2021; Lindinger et al., 2021). Kropf et al. (2021) (Kropf et al., 2021) engaged local stakeholders in a multi-step cognitive mapping approach to discuss climate change adaptation. In the process, they recorded the stakeholders' perceptions and discussed adaptation measures. Among the most discussed measures are (I) adjusting the current crop rotation, (II) improving irrigation efficiency, and (III) artificial aquifer recharge. Artificial recharge is part of a governmental project, which includes the construction of a canal to bring water from the Moson-Danube River into the Seewinkel region to artificially recharge the aquifer.

3.2.2 System Dynamics

SD is a method developed to model complex systems and the interactions within them. The method has proven useful for the simulation of complex environmental and water problems (Zomorodian et al., 2018). SD has been used extensively as a tool for water management as the interactions between hydrological systems, society and the environment can be built into the models. For example, SD has been implemented to improve water resources management (Correia de Araujo et al., 2019; Dong et al., 2019; Kotir et al., 2016; Mirchi et al., 2012; Sun et al., 2017), groundwater management (Barati et al., 2019), river management (Hassanzadeh et al., 2014; Rubio-Martin et al., 2020) and water management for climate change adaptation (Gohari et al., 2017).

SD models offer several advantages that can be exploited to support climate change adaptation processes. First, SD models can be developed fast and can integrate information provided by stakeholders. Second, they are visual, which makes them easier to understand even to individuals with no training in modelling and increases the interpretability of the results. Third, they usually compute results in relatively short time compared to other modelling methods (Zomorodian et al., 2018). This is a strong advantage when compared to purely hydrological models or hydro-economic models, which are computationally intensive. Because of the reasons mentioned above, SD models become a more favorable tool to test adaptation measures and communicate the results with stakeholders.

3.2.3 Historical Data

The SD model was calibrated using hydrological and climate data for the reference period 1981 to 2011. Groundwater level data recorded in boreholes and lake control-station data are available in the Austrian water portal (eHYD.gov.at). The lakes have measuring stations recording the fluctuations in the water depth at a daily scale. For the aquifer, daily groundwater level data from seventy measuring stations was normalized and averaged to get a single dataset.

The Austrian water portal also provided precipitation data from seven weather stations, located inside the basin, for the same reference period (1981 - 2011). Precipitation was averaged at a monthly basis for the whole region, as the model is not spatially distributed. The potential evapotranspiration data was calculated by using the Community Water Model (CWatM) (Burek et al., 2020) using the Penman-Monteith equation (Monteith, 1965).

3.2.4 Climate Projection Data

To simulate the region's condition under climate change, this study uses EURO-CORDEX data (Jacob et al., 2014) for three Representative Concertation Pathway (RCP) scenarios. The RCPs represent three possible climate change futures as proposed in the Fifth Assessment Report (AR5) of the IPCC. These scenarios depend on the amount of greenhouse gases emitted in the coming decades. In this study, we consider three RCPs: RCP 2.6, RCP 4.5 and RCP 8.5.

For climate services purposes, the EURO-CORDEX community recommends using the largest possible model ensemble in order to achieve robust results (Benestad et al., 2021). Consequently, a multi-model ensemble was used for each RCP (Appendix A). Each model ensemble member was fed individually into the system dynamics model. Monthly near-surface temperature (tas), precipitation (pr) and potential evapotranspiration (evspsblpot) data were used for each RCP. Tas and pr were directly taken from the ensemble members. Evspsblpot was calculated from daily tas, maximum near-surface temperature (tasmax) and minimum near-surface temperature (tasmin) using the method by Hargreaves & Samani (1985) (Hargreaves & Samani, 1985) provided by the python package xclim (Logan et al., 2021). Spatial averages over the Seewinkel region were calculated with pyweights fuction.

The direct use of climate data as input for impact models, however, is not recommended, as regional climate model (RCM) outputs may still have considerable systematic biases which could produce inaccurate results (Mendez et al., 2020). Imperfect conceptualization, discretization and spatial averaging within grid cells leads to bias errors between climate models and observations (Soriano et al., 2019). Therefore, most climate change impact studies require an additional processing step with bias correction methods before the RCM data can be used so their statistical properties are more similar to the ones observed (Galmarini et al., 2019; Mendez et al., 2020).

Because of this, the climate data was bias adjusted applying the correction method using standard deviation (Equation 1) presented by Bouwer et al. (2004) (Bouwer et al., 2004). By applying this method, the climate data is corrected against the observed average and also for the observed variance. The chosen baseline period is 1981 – 2005, as 1981 is the first year for which complete observational data is available and 2005 is the last year of the historical period of the climate models.

(1) $$a'_{cm,j} = \frac{(a_{cm,j} - \bar{a}_{cm,j})}{\sigma_{cm,j}} \times \sigma_{obs,j} + \bar{a}_{obs,j}$$

Where $a'_{cm,j}$ is the corrected climate parameter of a particular month "*j*". $a_{cm,j}$ is the uncorrected simulated climate parameter. $\bar{a}_{cm,j}$ is the average simulated climate parameter over the baseline period. $\sigma_{cm,j}$ is the standard deviation of the simulated parameter over the baseline period.

$\sigma_{obs,j}$ is the standard deviation of the observed climate parameter over the baseline period and $\bar{a}_{obs,j}$ is the average observed climate parameter over the baseline period.

3.2.5 The SD Model

The SD model (Figure 3.2) developed in this study is a deterministic lumped model with a monthly time step and it is forced with precipitation and evapotranspiration data. The model consists of six stocks. The first stock represents water stored in the upper soil layers. The soil infiltration is modeled based on the curve number method (Equation (2), (3) and (4)) (Boonstra, 1994). First, an initial curve number CN = 84 was selected because Seewinkel is mostly flat, has soils with high infiltration rates and crops are planted in rows. Afterwards, equation (2) is used to calculate the maximum soil water retention capacity (S) in millimeters.

(2) $$S = \frac{25400}{CN} - 254$$

Afterwards runoff (Q) is calculated using equation (3). According to the curve number method runoff only begins if precipitation is greater than 20% of S. This initial accumulation of 20%, accounts for water intercepted in surface depressions or by vegetation (Bos et al., 2009). With the runoff (Q) and precipitation (Pp) values, infiltration is calculated with equation (4).

(3) $$Q = \frac{(P-0.2S)^2}{(P+0.8S)} if P > 0.2S$$

(4) $$Infiltration = Pp - Q$$

Infiltration then fills the soil and is stored in that stock. Water leaves this stock either by evapotranspiration or as aquifer recharge. First, potential evapotranspiration is satisfied by the water stored in this soil reservoir, thus actual evapotranspiration can be smaller than the potential one. Aquifer recharge only happens when the water stored in the soil is equal or greater to S. Once water exceeds S the excess leaves as recharge.

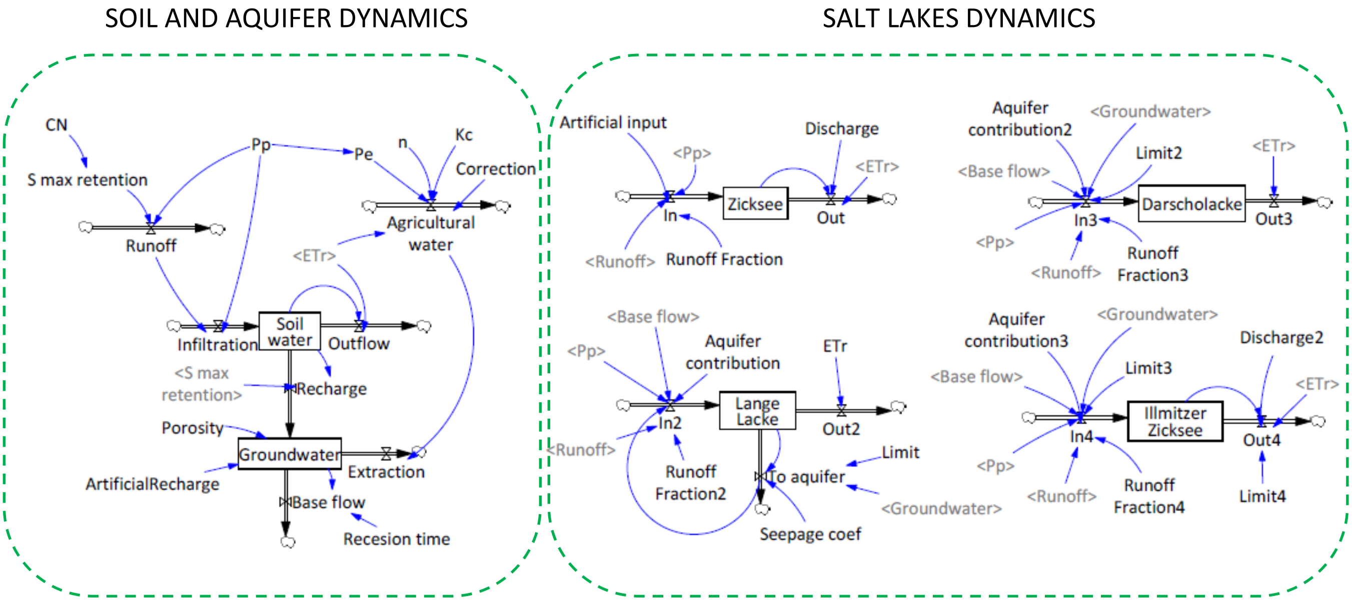

Figure 3.2. The SD model with its two sub-models. The sub-model on the left simulates the soil and aquifer dynamics as well as the irrigation water demand. The sub-model on the right models the lakes dynamics. A detailed description of the model's elements can be found in the model documentation in Appendix B.

The second stock represents the aquifer. In the aquifer stock, water leaves by two means either by baseflow feeding rivers or by extractions. The relation between aquifer stocks and baseflow is following a linear behavior (one recession coefficient). In Seewinkel, the agricultural industry is the only sector extracting water from the aquifer. The influence of agricultural water extraction on the aquifer dynamics is included in the upper right side of the model (Figure 3.2). Because of the unavailability of data needed to determine irrigation water use, the monthly irrigation water demand (IWD) is calculated using an irrigation demand equation (6) based on Brouwer & Heibloem (1986), Shen et al. (2013) and Wang et al. (2016) (Brouwer & Heibloem, 1986; Shen et al., 2013; Wang et al., 2016). The equation requires data on monthly evapotranspiration (ETP) and precipitation data (Pp) data. The effective precipitation (Pe) is calculated based on Pp with equation (5). The crop factor (Kc) is related to the crop type, the irrigation efficiency (η) represents the efficiency of the implemented irrigation method and a correction factor (cf).

(5)
$$Pe = 0.8 * Pp - 25 \; if \; Pp > 75$$
$$Pe = 0.6 * Pp - 10 \; if \; Pp < 75$$

(6)
$$IWD = \frac{(ETP*Kc)-Pe}{\eta * cf}$$

The crop factor (Kc) is unique for every crop and changes over the growing season. These values are usually available in manuals. In this study the values were obtained from Brouwer & Heibloem (1986) (Brouwer & Heibloem, 1986). As previously mentioned, the main crops in Seewinkel are potatoes, sugar beets, and corn. Because these crops have quite similar crop factors and vegetation periods, an average value was taken to simulate the crop water demand of the combined crop rotation (Appendix C).

As previously mentioned, the irrigation efficiency (η) is needed to calculate the IWD. According to Howell, (2003), common methods like, for example, sprinkler irrigation have efficiencies of 60 to 85% with average efficiency of 75%. Contrasting, water saving methods like drip irrigation have efficiencies of up to 95%. In the case of Seewinkel, farms rely on the moving big gun method, which has an efficiency of 55 to 75% with an average efficiency of 65%. This last value was selected to calculate the IWD of the study area.

The remaining stocks represent the four largest saline lakes. These lakes are the Zicksee, the Lange Lacke, the Darscholacke and the Ilmitzer Zicksee. The dynamic behavior of the saline lakes (Figure 3.2) is based on the extensive descriptions reported by Krachler et al. (2012) (Krachler et al., 2012). The lakes receive water from precipitation and runoff, and from the aquifer. Their common characteristic is that water mainly leaves the lakes through evaporation, which explains their saline nature. In some special cases, water leaves the lakes through discharge or infiltration. Since the beginning of the 20th century, each saline lake has been managed and modified in different ways. In the Lange Lacke, for example, water flows in both directions. Once the aquifer level drops, the water flows from the lake into the aquifer. The Zicksee, on the other hand, receives an annual artificial recharge of around 300,000 m3 coming for a well next to the lake.

3.2.6 SD Model Calibration

Calibration was done using the historical data and the optimization tool in the software Vensim developed by Ventana Systems. Vensim is a software designed to build and run SD models. The software optimizes user-defined model parameters to match historical observational data. Simulations are repeated until the parameters provide results that match the historical data. For the calibration, we used historical monthly groundwater and lakes fluctuations from the reference period 1981 - 2011. For the aquifer, we converted into anomalies and averaged the groundwater level from 70 measuring boreholes for the reference period 1981 – 2011 in order to have an overview of the aquifer behavior. In the case of the saline lakes, each of the four biggest lakes has a measuring station.

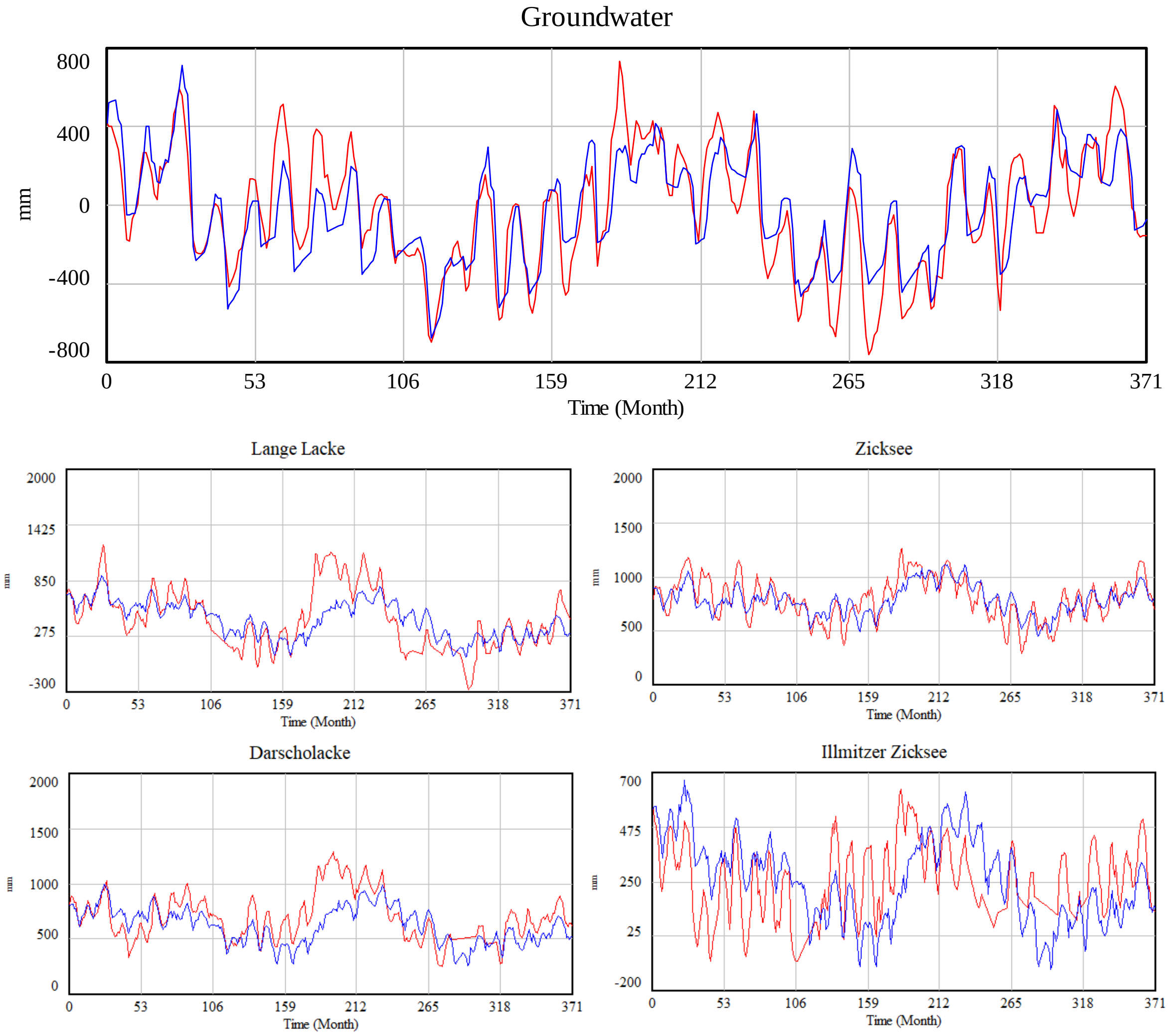

Figure 3.3. Output of the model (in blue) and the observational data (in red) for the Seewinkel aquifer showing the deviations around the historical mean (zero) and for the four biggest lakes.

After the calibration, the SD model developed in this work was able to reproduce the yearly and seasonal variations of the groundwater level. For the groundwater, the model had a correlation coefficient R^2 = 0.85 compared to observational data. Figure 3.3 shows the output of the model compared to the observational data. In the case of the saline lakes, the model has correlations of R^2= 0.75 for the Lange Lacke, R^2 = 0.77 for the Zicksee, R^2 = 0.66 for the Darscholacke and R^2 = 0.43 for the Ilmitzer Zicksee.

3.2.7 Simulating adaptation measures

Simulations were done using the Python library PySD to run the calibrated SD model. PySD is a tool that facilitates the integration of data science and SD models (Houghton & Siegel, 2015). Traditionally, SD Models can run only one simulation at the time. Meaning that only one input dataset and one output dataset can be computed per simulation. The modeler would have to manually change the input dataset to compute new results. However, with PySD it is possible to run simulations with input datasets composed of data ensembles. This means that the model can run multiple times, each time with a new input dataset. The results can then be automatically saved, processed and properly displayed.

PySD allowed us to run the SD model with each RCP data ensemble to simulate five possible adaptation scenarios. The five adaptation scenarios are based on the adaptation measures suggested by local stakeholders as presented by Kropf, (2021) (Kropf et al., 2021) and a business-as-usual scenario. These scenarios are; first, no adaptation measures implemented (BAU). Second, shift to less water demanding crops (CROP). Third, improve irrigation systems to increase irrigation efficiency (IRRI). Fourth, artificial recharge (RECH). Fifth, a combination of the CROP and IRRI scenario (COMB) (Appendix D). In total fifteen simulations were done using the multi-model ensemble climate projections. We have decided to test these measures because, according to the stakeholders, CROP, IRRI and RECH have the highest number of synergies and tradeoffs, with RECH being the most controversial (Kropf et al., 2021).

To simulate the implementation of an adaptation measure or the combination of two, one or more parameters were changed. In BAU, the simulations were run with no changes in the model parameters to simulate the present conditions. In CROP, the crop factors (Kc) and the growing periods were adjusted to simulate a new crop rotation consisting of faster growing crops with a lower water demand (Appendix E). The hypothetical crop rotation is based on less water-demanding crops such as sorghum, millet, soybeans, barley and lentils to substitute the three most grown crops (potatoes, sugar beets and corn).

In IRRI, the irrigation efficiency was increased to simulate a shift into more water-efficient irrigation methods. We simulate a shift into lateral move spray heads irrigation, which has an average efficiency of 85% according to Howell, (2003) (Howell, 2003) by changing the efficiency in the irrigation demand equation (5) from 0.65 to 0.85. RECH aims to simulate the implementation of artificial aquifer recharge; a measures similar to a project proposed by the government of Burgenland. The project proposed the construction of a canal to connect Seewinkel to the Moson-Danube, an arm of the Danube in Hungary. The water brought into the region could be used to artificially recharge the aquifer in Seewinkel. In our scenario we simulate a scenario where 3.75 M m^3/month (ca. 6.54 mm/month) will be diverted into Seewinkel and used to recharge the aquifer (ORF, 2021). Finally, COMB simulates a scenario in which farms adapt to climate change by combining IRRI and CROP. To simulate this, the irrigation efficiency was increased to 0.85 and the Kc changed to simulate the less water-demanding crop rotation mentioned above.

3.3. RESULTS

The modelling results are presented in this section. The dynamic behavior of irrigation demand (Figure 3.4), the aquifer (Figure 3.5) and the salt lakes (Figure 3.6) are used as reference parameters to compare the effectiveness of the adaptation measures. BAU represents the baseline to which IRRI, RECH and CROP and COMB are compared. The ranking of the adaptation measures is also presented in this section based on the simulation results.

3.3.1 Irrigation demand under climate change and adaptation scenarios.

The results (Figure 3.4) show that under all RCPs, COMB is the most efficient measure to reduce the IWD by an average of 40% compared to BAU. The IRRI, where farmers increase the efficiency of their irrigation methods, is almost as effective as CROP for all RCP. IRRI and CROP both reduce the IWD by an average of 23% compared to BAU. RECH has a direct effect on the available water but it does not influence the irrigation demand or the decisions taken by farmers. Therefore, it does not have any effect on the IWD. Only CROP and IRRI, or a combination of those two, reduce the IWD.

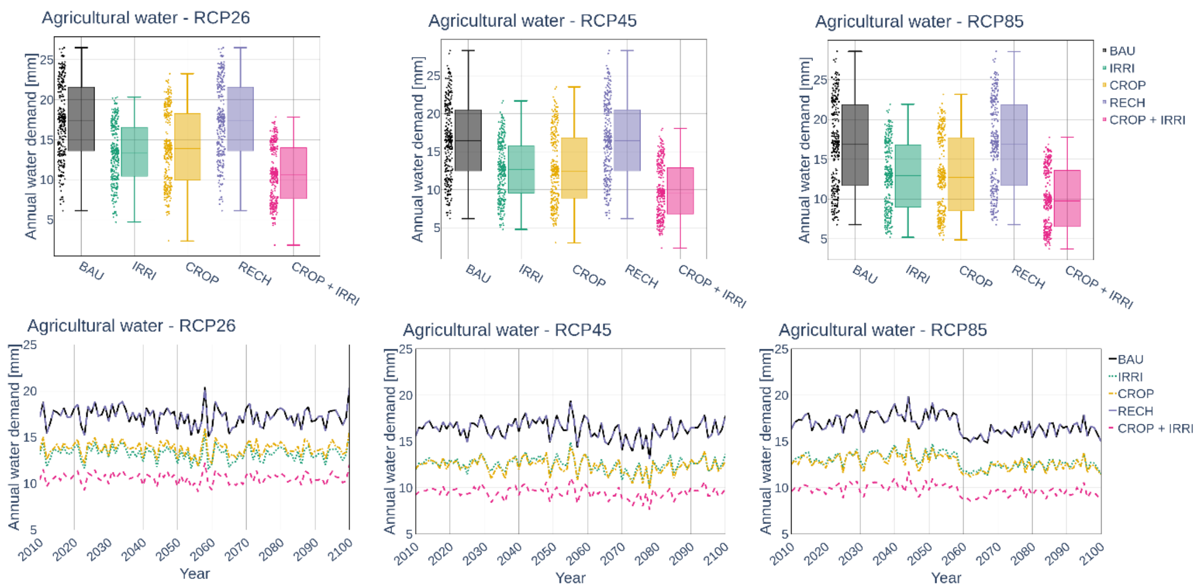

Figure 3.4. The average annual IWD under three RCP scenarios and the effect of the adaptation scenarios on the water demand for the reference period (2010-2100).

3.3.2 Aquifer dynamics under climate change and climate change adaptation scenarios.

For all RCPs, the aquifer shows an average drop below the historical average (zero) of 0.90 m in BAU, a scenario simulating a future where no adaptation measures are implemented in the region. For the RCP 2.6 the aquifer shows a stable trend. For the RCP 8.5 and the RCP 4.5 the aquifer shows an increasing trend after 2060 (Figure 3.5).

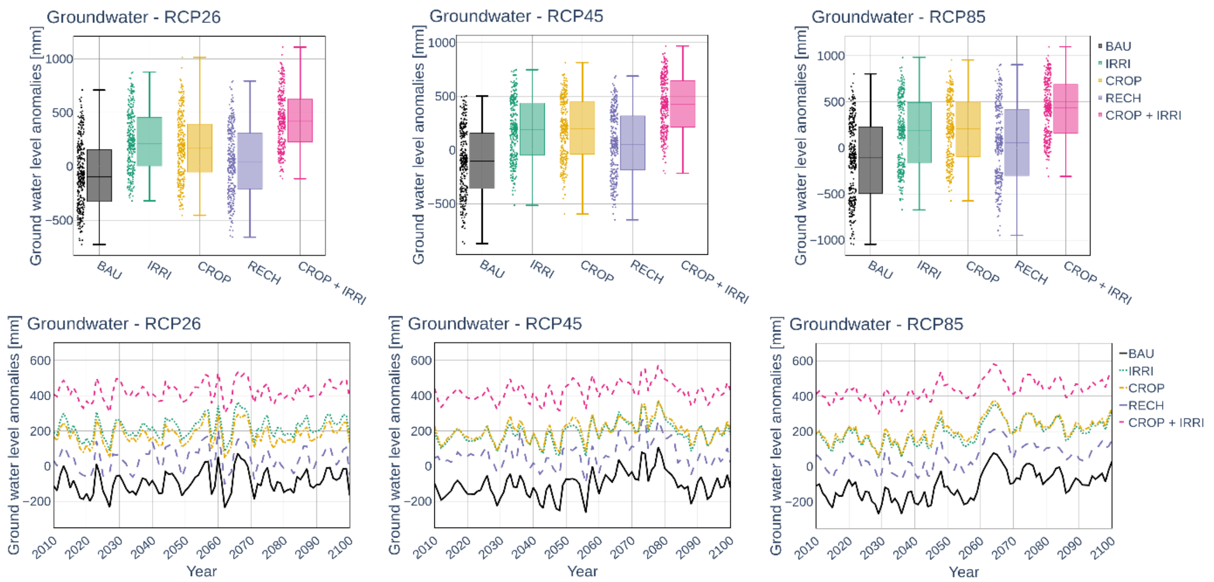

Figure 3.5. Aquifer level under three RCP scenarios and four adaptation scenarios. The zero represents the historical average of the aquifer.

All of the adaptation measures are effective and promote an increase in the ground water level (Figure 3.5). The most effective measure being COMB, which promotes an average increase in the stored volume of about 0.43 m above the historical average (zero) for all RCPs. IRRI and CROP followed. Both, the IRRI and CROP, scenarios would promote an average increase of 0.20 m above the historical average of the aquifer for all RCPs. Lastly, RECH was the least effective by promoting only a slight increase of 0.06 m above the historical average of the aquifer for all RCPs.

3.3.3 Salt lakes dynamics under climate change and adaptation scenarios.

For the RCP 2.6 and the RCP 4.5 the lakes follow a decreasing trend until 2060 when this trend changes to a drastically incremental trend. For the RCP 8.5 the Lange Lacke and the Darscholacke completely dry out before the year 2030 and remain dry up until 2060 after which they could recover. For the RCP 8.5 the Ilmitzer Zicksee dries out in the decade of 2050. The Zicksee does not dry out under any of the RCPs, possibly because it is the only lake that receives a continuous artificial recharge as it is no longer connected to the aquifer. Nevertheless, the Zicksee also shows the drastical increase after 2060.

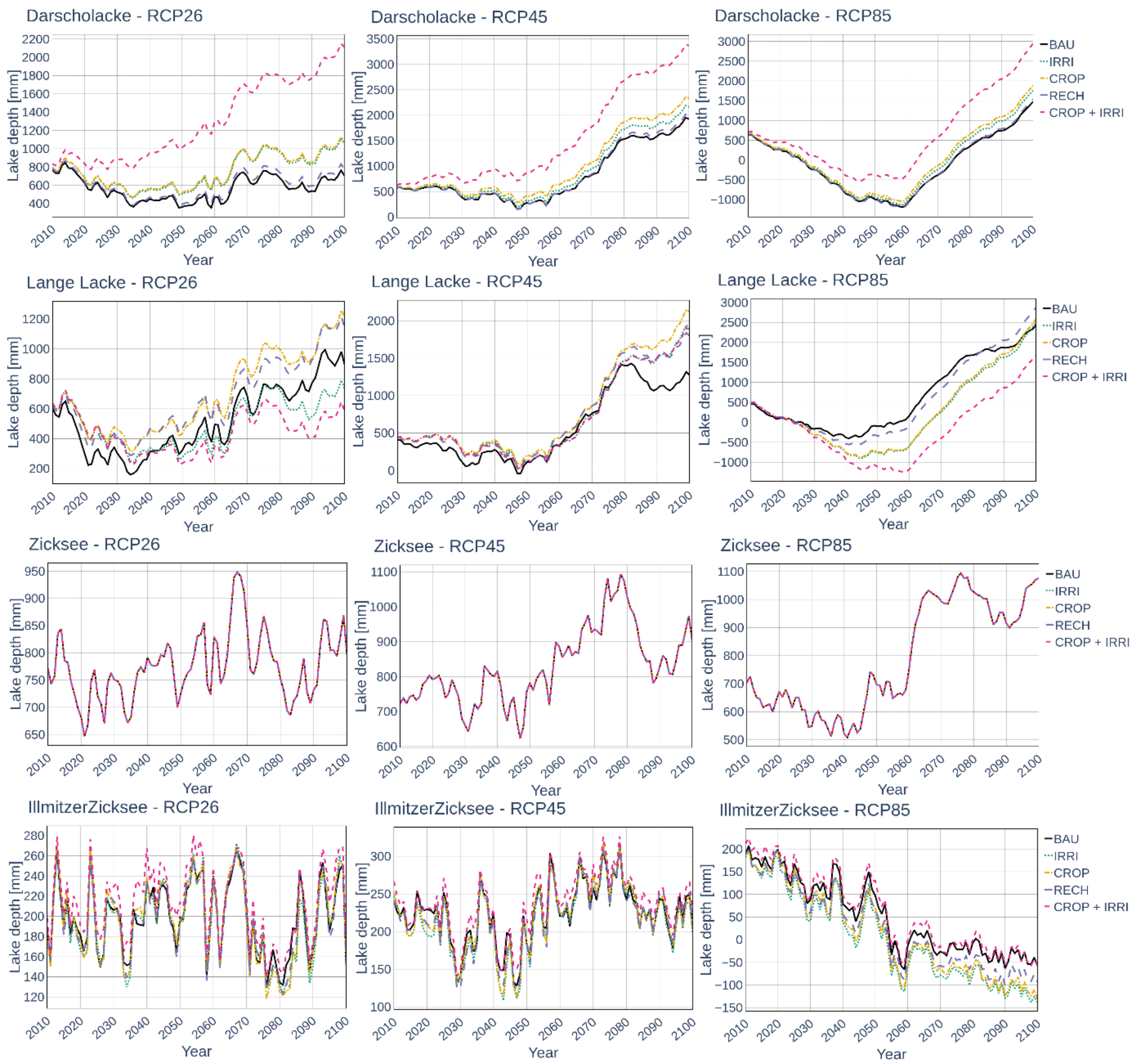

Figure 3.6. Salt lakes depth under three RCP scenarios and the four adaptation scenarios. In the first row the Darscholacke, the second row the Lange Lacke, the third row the Zicksee and the forth row the Ilmitzer Zicksee.

In regards to the adaptation measures, there is a difference in effectiveness on the lakes. In the Darscholacke (first row Figure 3.6), the most effective adaptation measure is COMB followed by CROP, IRRI and lastly RECH. This is valid for all RCPs. In the Lange Lacke (second row, Figure 3.6), the most effective measure is CROP, followed by RECH, IRRI and lastly COMB in the RCP 2.6. In the RCP 4.5 the most effective measures are CROP, followed by IRRI and COMB and lastly RECH. For the RCP 8.5 the measures seem to have no positive effect. The adaptation scenarios do not affect the Zicksee (third row, Figure 3.6) as it is not connected to the aquifer. The Ilmitzer Zicksee (fourth row, Figure 3.6) is not considerably affected by any of the adaptation measures but the COMB.

3.3.4 Ranking of the adaptation measures

In this section, we present a ranking of the adaptation measures based on their effectiveness to improve the resilience of the different water bodies in Seewinkel and their effectiveness to reduce

IWD. The adaptation measures are ranked on a scale from one to four, with one being the most effective adaptation measures and four the least effective for that particular parameter under a particular RCP (Table 3.1).

Table 3.1. Adaptation measures ranked by how effective they were to improve the water bodies or reduce the IWD under the three RCP scenarios. N/E stands for "no effect".

RCP	Scenario	Aquifer	Irrigation Demand	Darscholacke	Lange Lacke	Ilmitzer Zicksee	Zicksee	Average
RCP 2.6	CROP	3	3	2	1	N/E	N/E	2.25
	IRRI	2	2	2	3	N/E	N/E	2.25
	RECH	4	N/E	3	2	N/E	N/E	3.00
	COMB	1	1	1	4	1	N/E	1.75
RCP 4.5	CROP	2	2	2	1	N/E	N/E	1.75
	IRRI	3	3	3	2	N/E	N/E	2.75
	RECH	4	N/E	4	3	N/E	N/E	3.67
	COMB	1	1	1	2	1	N/E	1.25
RCP 8.5	CROP	2	2	2	N/E	N/E	N/E	2
	IRRI	3	3	2	N/E	N/E	N/E	2.67
	RECH	4	N/E	3	N/E	N/E	N/E	3.50
	COMB	1	1	1	N/E	1	N/E	1

In Table 3.2 we present the results after ranking the adaptation measures and obtaining an average of their effectiveness. Our results show that COMB is the most beneficial for both, the water bodies and the irrigation demand, followed by CROP, then by IRRI and lastly by RECH.

Table 3.2. The adaptation measures were ranked by how effective they were to improve the water bodies or reduce the IWD under the three RCP scenarios. This table shows the final ranking based on an average across all RCPs.

Scenario	RCP 2.6	RCP 4.5	RCP 8.5	Average
CROP	2.25	1.75	2	2.00
IRRI	2.25	2.75	2.67	2.56
RECH	3.00	3.67	3.5	3.39
COMB	1.75	1.25	1	1.33

3.4. DISCUSSION

3.4.1 Effectiveness of the suggested adaptation measures.

The results of this study show that combination of a shift to less water-demanding crops and increasing irrigation efficiency is the most beneficial approach to reduce the IWD under all climate change scenarios. While all of the adaptation measures analyzed were effective to reduce aquifer degradation, the implementation of IRRI and CROP still had a greater effect on the water resources compared to RECH. Because of this, in the case of Seewinkel, our results show that farmers are the most influential stakeholders. However, this group should not be held as the only responsible for climate change adaptation as usually the implementation of adaptation measures requires substantial investments and strong shifts within the local economy and farm structures. Additionally, the project suggested by the local government on which RECH is based, has proved, under our analysis, to be the less beneficial measure for the aquifer and the saline lakes, and it does not have any effect on the IWD. This project might also imply large investments, which could instead be used to support farmers implementing changes to their irrigation systems and crop rotations.

3.4.2 Performance of adaptation measures.

Changing or diversifying the crop rotation is a commonly suggested adaptation measure as it increases the resilience to climate change and drought (EEA, 2019; European Commission, 2018; IPCC, 2022). Adapted crops can help secure yields and the cost of implementing the changes is mainly dependent on the price of the new seeds and the structural changes needed at the farm level (EEA, 2019). Intercropping, for example, has been shown to increase production, soil quality and insect biodiversity (IPCC, 2019). However, according to Kropf et al. (2021) (Kropf et al., 2021), stakeholders in Seewinkel perceive that a change to drought tolerant crops on larger areas could increase the demand for groundwater for irrigation. A belief that our study has proven to be incorrect. Our study has shown that changing crops is an effective way to adapt to climate change as it reduces IWD and thus reduces the pressure on local water resources. This measure is effective for the three RCPs. However, implementing these changes has additional challenges. Kropf et al. (2021) (Kropf et al., 2021) found that stakeholders in Seewinkel perceive that a new crop rotation could have economic trade-off such as increase the workload or investments in new farming equipment. Additionally, for new crop rotations to be successful, they should be compatible with the market demand, promote soil formation and be economically sustainable (Drastig et al., 2016; Schipper, 2020; Valencia Cotera et al., 2022). If the new crops are not compatible with the market demand, farmers could become more economically vulnerable, thus causing maladaptation. Designing a new crop rotation for Seewinkel consisting of less water-demanding crops that are also economically feasible represents research opportunity for future studies.

Improved irrigation techniques can increase farmers' adaptive capacity (Datta & Behera, 2022; Heumesser et al., 2012; IPCC, 2022). According to Kropf et al. (2021) (Kropf et al., 2021), some stakeholders in Seewinkel believed that increasing the irrigation efficiency would only have a small effect in reducing groundwater use for agriculture. A belief that our study has proven to be incorrect. Our results show that by increasing the irrigation efficiency, farmers in Seewinkel could strongly reduce their IWD under the conditions that they keep the same cropping pattern and not expand their irrigated area. This could allow them to continue using irrigation to cope with dry periods while at the same time reduce the pressure on the local aquifer. However, substituting the current irrigation systems implies a strong investment. Subsidizing these systems could promote their implementation and support farmers (Heumesser et al., 2012). It is also important to consider that reluctance to improve the efficiency of irrigation could prove to be economically unsustainable in the long run. Mainly because intensive irrigation could lead to higher energy use which in turn causes higher emissions (Zhao et al., 2018) and increases the production costs (Valencia Cotera et al., 2022). Especially in Seewinkel, where the majority of the water pumps are powered using fossil fuels (Kropf et al., 2021). Overuse of irrigation could also promote soil salinization and bioaccumulation of toxins (Mcdermid et al., 2021), increased fertilizer use and fertilizer leaching (Bwambale et al., 2022; Mcdermid et al., 2021). Because of this, relying only on current irrigation methods could cause a rebound in vulnerability as agriculture might become unprofitable. Further analysis is required to study the economic and energy cost of irrigation in Seewinkel under climate change. These studies could also propose viable ways to promote and incentivize a shift to more water efficient irrigation methods.

Artificial recharge has proven to be an effective method to promote sustainable groundwater use and increase the aquifer reserves (Javadi et al., 2021; Prabhu & Venkateswaran, 2015). Our results have shown that artificial recharge was the least effective single measure to increase and protect water resources in Seewinkel. If implemented, it still could however improve the state of the aquifer and the salt lakes. Artificial recharge is also effective under all RCPs. However, this is the only measure, which does not reduce the IWD and it could be the most expensive. While this measure has mainly an effect on the local water resources, it could also help to improve the resilience of farms by increasing the water supply. Additionally, according to Kropf et al. (2021) (Kropf et al., 2021) stakeholders in Seewinkel who oppose this measure believe that changing crops would be more effective, a belief that our study has confirmed. Finally, artificial recharge also presents additional challenges as it could lead to maladaptation by causing a shift in vulnerability or a degradation of the common good. Since more water could be available in Seewinkel but the water extractions from the Moson-Danube could degrade the resource or have negative effects somewhere else downstream.

3.4.3 Strengths and drawbacks of the SD Model

The model serves as a tool to compare climate change adaptation strategies but it is not intended to entirely substitute hydrological models. However, we have identified that the model has four main advantages that are beneficial for climate change adaptation analysis. First, our SD model allows the user to test and evaluate the effect of climate change adaptation measures. Second, thanks to the implementation of PySD the model can run using climate data ensembles to reduce uncertainty about the future climate scenarios. Third, due to its modular design, the model could be coupled to other SD sub-models to create larger, more sophisticated models. Fourth, the SD model could be reused and recalibrated for other similar regions. Because of these advantages, we believe that our model can serve as the groundwork for similar future research.

The model has, however, two disadvantages. First, when compared to traditional hydrological models it falls short of detail. Second, the model does not consider the socio-economic effects of adaptation. Therefore, we propose two potential ways to advance this research. To address the first drawback we propose to give the model spatial distribution. This could be possibly done by separating the aquifer into smaller regions and afterwards recalibrating the model for each individual zone to include horizontal mass exchange between the zones. The spatial distribution could be done directly in Vensim or with Python. To address the second disadvantage, we propose the development of a socio-economic sub-model to simulate the economic effect that the adaptation measures could have on the local economy. The development of the socio-economic model would be research intensive, as it should be based on local information provided by stakeholders.

Finally, it should be considered that developing a complete water resources management model is a highly challenging task and it is extremely challenging to include all factors, feedbacks and relationships. We believe however that our model offers an acceptable reflection of the current trends in Seewinkel but we encourage others to expand the boundaries and limitations of our model with further research.

3.5. CONCLUSION

Analyzing the systemic effect of adaptation measures is highly beneficial for climate change adaptation. First, it bridges a common knowledge gap by showing how effective the adaptation measures are to reduce the negative effects of climate change. This in turn can help stakeholders to develop better adaptation plans by first implementing high-impact measures and by avoiding costly measures with weak effects. This could consequently help avoid maladaptation. Second, it could help change the stakeholders' perspectives. In Seewinkel, stakeholders hold incorrect views about the efficacy of the adaptation measures. This could lead them to take incorrect actions or avoid adaptation. By presenting evidence of the efficiency of adaptation measures, their views could be changed to promote adaptation. Thirdly, our study has confirmed that, adapting agriculture in Seewinkel to climate change has additional benefits. A major advantage of adaptation is that it can help preserve the aquifer and the unique habitat of saline lakes.

In Seewinkel, shifting to less water-demanding crops and improving irrigation efficiency are highly efficient strategies to reduce IWD and safeguard the aquifer. As a result, farmers are the most influential actors. However, this group should not be seen as the only responsible. Adaptation measures usually require high initial investments and systemic changes that can adversely affect farms and local economies. Farmers should therefore receive support from decision makers in order to achieve adaptation goals at the national and regional levels. Finally, under this analysis, the proposed local project to artificially recharge the aquifer represents the least beneficial measure for the aquifer, since does not reduce extractions, has less noticeable effects and it depends on water from the Danube, which is a shared resource.

There are two innovative aspects to this study. First, it presents an original hydrological model, which can be used to perform similar analyses in other regions. This study has shown that, in regions of up to 450 km^2, the developed SD model can be highly correlated with unconfined aquifers (R2 =

0.85); if good hydrological and climate data are available. This original model could be coupled to other SD models to perform more complex socio-economic analyses with a hydrological component. Second, this is the first study in Seewinkel to perform a systemic analysis of the effects that climate change adaptation would have. Previous studies have focused on the aquifer, the state of the saline lakes and on the farmers perceptions. However, no previous study had brought the three aspects together to perform a systemic analysis.

AUTHOR CONTRIBUTIONS

Conceptualization, R.V.C, L.G. and R.K.S; data curation, L.L., L.G. and R.V.C; formal analysis, R.V.C.; investigation, R.V.C; Methodology R.V.C, Supervision L.G., R.K.S, C.N. and M.M.C.; writing – original draft, R.V.C; writing – review and editing, L.G, R.K.S, L.G., C.N, L.L and M.M.C.

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REFERENCES

Asseng, S., Ewert, F., Martre, P., Rötter, R. P., Lobell, D. B., Cammarano, D., Kimball, B. A., Ottman, M. J., Wall, G. W., White, J. W., Reynolds, M. P., Alderman, P. D., Prasad, P. V. V., Aggarwal, P. K., Anothai, J., Basso, B., Biernath, C., Challinor, A. J., De Sanctis, G., … Zhu, Y. (2015). Rising temperatures reduce global wheat production. *Nature Climate Change*, *5*(2), 143–147. https://doi.org/10.1038/nclimate2470

Barati, A. A., Azadi, H., & Scheffran, J. (2019). A system dynamics model of smart groundwater governance. *Agricultural Water Management*, *221*(December 2018), 502–518. https://doi.org/10.1016/j.agwat.2019.03.047

Benestad, R., Buonomo, E., Gutiérrez, J. M., Haensler, A., Hennemuth, B., Illy, T., Jacob, D., Keup-thiel, E., Katragkou, E., Kotlarski, S., Nikulin, G., Otto, J., Remke, T., Sieck, K., Sobolowski, S., Szabó, P., Teichmann, C., Vautard, R., Weber, T., & Zsebeházi, G. (2021). *Guidance for EURO-CORDEX climate* *projections data use* (pp. 1–29). https://www.climate-service-center.de/imperia/md/content/csc/cordex/guidance_for_euro-cordex_climate_projections_data_use__2021-02.pdf

Boonstra, J. (1994). Estimating Peak Runoff Rates. In *The Handbook of Applied Hydrology* (pp. 121–144). McGraw Hill New York.

Bos, M. G., Kselik, R. A. L., Allen, R. G., & Molden, D. J. (2009). Effective Precipitation. In *Water Requirements for Irrigation and the Environment* (pp. 81–101). Springer. https://doi.org/https://doi.org/10.1007/978-1-4020-8948-0

Bouwer, L. M., Aerts, J. C. J. H., Coterlet, G. M. van der, Giesen, N. van de, Gieske, A., & Mannaerts, C. (2004). Evaluating Downscaling Methods for Preparing Global Circulation Model (GCM) Data for Hydrological Impact Modelling. In J. Aerts & P. Droogers (Eds.), *Climate Change in Contrasting River Basins* (pp. 25–47).

Brás, T. A., Seixas, J., Carvalhais, N., & Jagermeyr, J. (2021). Severity of drought and heatwave crop losses tripled over the last five decades in Europe. *Environmental Research Letters*, *16*(6). https://doi.org/10.1088/1748-9326/abf004

Brouwer, C., & Heibloem, M. (1986). *Irrigation Water Management: Irrigation Water Needs. Training Manual no. 3*. FAO.

Bundesministerium für Landwirtschaft Regionen und Tourismus. (2021). *Wasserschatz Österreichs*. https://info.bmlrt.gv.at/dam/jcr:6c8210bb-6987-4ec4-8321-589612d60d0b/Wasserschatz_Ergebnistabelle.xlsx

Burek, P., Satoh, Y., Kahil, T., Tang, T., Greve, P., Smilovic, M., & Guillaumot, L. (2020). Development of the Community Water Model (CWatM v1 . 04) – a high-resolution hydrological model for global and regional assessment of integrated water resources management. *Geoscientific Model Development*, *13*, 3267–3298.

Bwambale, E., Abagale, F. K., & Anornu, G. K. (2022). Smart irrigation monitoring and control strategies for improving water use efficiency in precision agriculture: A review. *Agricultural Water Management*, *260*. https://doi.org/10.1016/j.agwat.2021.107324

Cammalleri, C., Naumann, G., Mentaschi, L., Formetta, G., Forzieri, G., Gosling, S., Bisselink, B., De Roo, A., & Feyen, L. (2020). Global warming and drought impacts in the EU. *Publications Office of the European Union*. https://doi.org/10.2760/597045

Correia de Araujo, W., Oliveira Esquerre, K. P., & Sahin, O. (2019). Building a System Dynamics Model to Support Water Management : A Case Study of the Semiarid Region in the Brazilian Northeast. *Water*, *11*.

Dalin, C., Wada, Y., Kastner, T., & Puma, M. J. (2017). Groundwater depletion embedded in international food trade. *Nature*, *543*. https://doi.org/10.1038/nature21403

Datta, P., & Behera, B. (2022). Assessment of adaptive capacity and adaptation to climate change in the farming households of Eastern Himalayan foothills of West Bengal , India. *Environmental Challenges*, *7*(July 2021), 100462. https://doi.org/10.1016/j.envc.2022.100462

Dong, Q., Zhang, X., Chen, Y., & Fang, D. (2019). *Dynamic Management of a Water Resources-Socioeconomic-Environmental System Based on Feedbacks Using System Dynamics*. 2093–2108.

Drastig, K., Prochnow, A., Libra, J., Koch, H., & Rolinski, S. (2016). Irrigation water demand of selected agricultural crops in Germany between 1902 and 2010. *Science of the Total Environment*, *569–570*, 1299–1314. https://doi.org/10.1016/j.scitotenv.2016.06.206

EEA. (2019). *Climate change adaptation in the agriculture sector in Europe*. *04/2019*.

EEA. (2021). *Water and agriculture: towards sustainable solutions*. Publications Office of the European Union. https://doi.org/10.2800/73735

European Commission. (2018). *A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy*.

FAO. (2018). *Transforming food and agriculture to achieve the SDGs*.

FAO. (2021). The impact of disasters and crises on agriculture and food security: 2021. In *The impact of disasters and crises on agriculture and food security: 2021*. https://doi.org/10.4060/cb3673en

Galmarini, S., Cannon, A. J., Ceglar, A., Christensen, O. B., Noblet-ducoudré, N. De, Dentener, F., Doblas-Reyes, F. J., Dosio, A., Gutierrez, J. M., Iturbide, M., Jury, M., Lange, S., Loukos, H., Maiorano, A., Maraun, D., McGinnis, S., Nikulin, G., Riccio, A., Sanchez, E., … Zampieri, M. (2019). Adjusting climate model bias for agricultural impact assessment : How to cut the mustard. *Climate Services*, *13*, 65–69. https://doi.org/10.1016/j.cliser.2019.01.004

Gleeson, T., Wada, Y., Bierkens, M. F. P., & Beek, L. P. H. Van. (2012). Water balance of global aquifers revealed by groundwater footprint. *Nature*, *488*, 7–10. https://doi.org/10.1038/nature11295

Gohari, A., Mirchi, A., & Madani, K. (2017). System Dynamics Evaluation of Climate Change Adaptation Strategies for Water Resources Management in Central Iran. *Water Resources Management*. https://doi.org/10.1007/s11269-017-1575-z

Hargreaves, G. H., & Samani, Z. A. (1985). Reference Crop Evapotranspiration from Temperature. *Applied Engineering in Agriculture*, *1*(2), 96–99. https://doi.org/10.13031/2013.26773

Hassanzadeh, E., Elshorbagy, A., Wheater, H., & Gober, P. (2014). Managing water in complex systems: An integrated water resources model for Saskatchewan, Canada. *Environmental Modelling and Software*, *58*, 12–26. https://doi.org/10.1016/j.envsoft.2014.03.015

Heumesser, C., Fuss, S., Szolgayová, J., Strauss, F., & Schmid, E. (2012). Investment in Irrigation Systems under Precipitation Uncertainty. *Water Resources Management*, *26*(11), 3113–3137. https://doi.org/10.1007/s11269-012-0053-x

Houghton, J., & Siegel, M. (2015). A dvanced data analytics for system dynamics models using PySD. *Proceedings of the 33rd International Conference of the System Dynamics Society.*

Howell, T. A. (2003). Irrigation Efficiency. In *Encyclopedia of Water Science*. Marcel Dekker, Inc. https://doi.org/10.1081/E-EWS 120010252

Huang, S., Wortmann, M., Duethmann, D., Menz, C., Shi, F., Zhao, C., Su, B., & Krysanova, V. (2018). Adaptation strategies of agriculture and water management to climate change in the Upper Tarim River basin, NW China. *Agricultural Water Management*, *203*, 207–224. https://doi.org/10.1016/j.agwat.2018.03.004

Iglesias, A., & Garrote, L. (2015). Adaptation strategies for agricultural water management under climate change in Europe. *Agricultural Water Management*, *155*, 113–124. https://doi.org/10.1016/j.agwat.2015.03.014

Ionita, M. (2020). On the curious case of the recent decade , mid-spring precipitation de fi cit in central Europe. *Npj Climate and Atmospheric Science*, 1–10. https://doi.org/10.1038/s41612-020-00153-8

IPCC. (2019). Climate Change and Land. In *An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*.

IPCC. (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen,. *Cambridge University Press*, *In Press*, 3949. https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf

IPCC. (2022). Chapter 4: Water. In *Sixth Assessment Report*.

Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O. B., Bouwer, L. M., Braun, A., Colette, A., Déqué, M., Georgievski, G., Georgopoulou, E., Gobiet, A., Menut, L., Nikulin, G., Haensler, A., Hempelmann, N., Jones, C., Keuler, K., Kovats, S., … Yiou, P. (2014). EURO-CORDEX: new high-resolution climate change projections for European impact research. *Regional Environmental Change*, *14*(2), 563–578. https://doi.org/10.1007/s10113-013-0499-2

Javadi, S., Saatsaz, M., Shahdany, S. M. H., Neshat, A., Ghordoyee, S., & Akbari, S. (2021). Geoscience Frontiers A new hybrid framework of site selection for groundwater recharge. *Geoscience Frontiers*, *12*(4), 101144. https://doi.org/10.1016/j.gsf.2021.101144

Karner, K., Mitter, H., & Schmid, E. (2019). The economic value of stochastic climate information for agricultural adaptation in a semi-arid region in Austria. *Journal of Environmental Management*, *249*(August), 109431. https://doi.org/10.1016/j.jenvman.2019.109431

Kotir, J. H., Smith, C., Brown, G., Marshall, N., & Johnstone, R. (2016). A system dynamics simulation model for sustainable water resources management and agricultural development in the Volta River Basin, Ghana. *Science of the Total Environment*, *573*, 444–457. https://doi.org/10.1016/j.scitotenv.2016.08.081

Krachler, R., Korner, I., Kirschner, A., Dvorak, M., Milazowszky, N., Rabitsch, W., Werba, F., & Zulka, K. P. (2012). *Die Salzlacken des Seewinkels: Erhebung des aktuellen ökologischen Zustandes sowie Entwicklung individueller Lackenerhaltungskonzepte für die Salzlacken des Seewinkels (2008 – 2011)*.

Kropf, B., Schmid, E., & Mitter, H. (2021). Multi-step cognitive mapping of perceived nexus relationships in the Seewinkel region in Austria. *Environmental Science and Policy*, *124*(April), 604–615. https://doi.org/10.1016/j.envsci.2021.08.004

Leitner, M., Babcicky, P., Schinko, T., & Glas, N. (2020). Climate Risk Management The status of climate risk management in Austria . Assessing the governance landscape and proposing ways forward for comprehensively managing flood and drought risk. *Climate Risk Management*, *30*(October), 100246. https://doi.org/10.1016/j.crm.2020.100246

Lindinger, H., Grath, J., Brielmann, H., Schönbauer, A., Gattringer, I., Formanek, C., Broer, M., Rosmann, T., Holler, C., Szerencsits, M., Neunteufel, R., Sinemus, N., Grunert, M., & Germann, V.

(2021). Wasserschatz Österreichs. Grundlagen für nachhaltige Nutzungen des Grundwassers Hintergrunddokument. In *Bundesministerium für Landwirtschaft, Regionen und Tourisimus*.

Logan, T., Bourgault, P., Smith, T. J., Huard, D., Biner, S., Labonté, M.-P., Rondeau-Genesse, G., Fyke, J., Aoun, A., Roy, P., Ehbrecht, C., Caron, D., Stephens, A., Whelan, C., Low, J.-F., & Lavoie, J. (2021). Ouranosinc/xclim: v0.31.0 (v0.31.0). *Zenodo*. https://doi.org/10.5281/zenodo.5649661

Ludwig, F., Slobbe, E. Van, & Cofino, W. (2014). Climate change adaptation and Integrated Water Resource Management in the water sector. *Journal of Hydrology*, *518*, 235–242. https://doi.org/10.1016/j.jhydrol.2013.08.010

Magyar, N., Hatvani, I. G., Arató, M., Trásy, B., Blaschke, A. P., & Kovács, J. (2021). A new approach in determining the decadal common trends in the groundwater table of the watershed of lake "Neusiedlersee." *Water*, *13*(3), 1–17. https://doi.org/10.3390/w13030290

Mcdermid, S. S., Mahmood, R., Hayes, M. J., Bell, J. E., & Lieberman, Z. (2021). Minimizing trade-offs for sustainable irrigation. *Nature Geoscience*, *14*(October). https://doi.org/10.1038/s41561-021-00830-0

Mendez, M., Maathuis, B., Hein-Griggs, D., & Alvarado-Gamboa, L.-F. (2020). Performance Evaluation of Bias Correction Methods for Climate Change Monthly Precipitation Projections over Costa Rica. *Water*. https://doi.org/10.3390/w12020482

Mirchi, A., Madani, K., Jr, D. W., & Ahmad, S. (2012). *Synthesis of System Dynamics Tools for Holistic Conceptualization of Water Resources Problems*. 2421–2442. https://doi.org/10.1007/s11269-012-0024-2

Mitter, H., & Schmid, E. (2021a). Informing groundwater policies in semi-arid agricultural production regions under stochastic climate scenario impacts. *Ecological Economics*, *180*(June 2020), 106908. https://doi.org/10.1016/j.ecolecon.2020.106908

Mitter, H., & Schmid, E. (2021b). Informing groundwater policies in semi-arid agricultural production regions under stochastic climate scenario impacts. *Ecological Economics*, *180*(November 2020), 106908. https://doi.org/10.1016/j.ecolecon.2020.106908

Montanari, A., Young, G., Savenije, H. H. G., Hughes, D., Wagener, T., Ren, L. L., Koutsoyiannis, D., Cudennec, C., Toth, E., Grimaldi, S., Blöschl, G., Sivapalan, M., Beven, K., Gupta, H., Hipsey, M., Schaefli, B., Arheumer, B., Boegh, E., Schymanski, S. J., … Belyaev, V. (2013). "Panta Rhei — Everything Flows ": Change in hydrology and society — The IAHS Scientific Decade 2013 – 2022. *Hydrological Sciences Journal*, *58*(6), 1256–1275. https://doi.org/10.1080/02626667.2013.809088

Monteith, J. L. (1965). Evaporation and environment. *Symposia of the Society for Experimental Biology*, *19*, 205–234.

Naumann, G., Cammalleri, C., Mentaschi, L., & Feyen, L. (2019). Increased economic drought impacts in Europe with anthropogenic warming. *Nature Climate Change*. https://doi.org/10.1038/s41558-021-01044-3

ORF. (2021). *Land will Donau-Wasser für Seewinkel*. https://burgenland.orf.at/stories/3095447/

Prabhu, M. V., & Venkateswaran, S. (2015). Delineation of Artificial Recharge Zones Using Geospatial Techniques In Sarabanga Sub Basin Cauvery River , Tamil Nadu. *Aquatic Procedia*, *4*(Icwrcoe), 1265–1274. https://doi.org/10.1016/j.aqpro.2015.02.165

Rechnungshof Österreich. (2020). *Nationalpark Neusiedler See - Seewinkel*. https://www.rechnungshof.gv.at/rh/home/home/Nationalpark_Neusiedler_See.pdf

Rubio-Martin, A., Pulido-Velazquez, M., Macian-Sorribes, H., & Garcia-Prats, A. (2020). System Dynamics Modeling for Supporting Drought-Oriented Management of the Jucar River. *Water*, *12*. https://doi.org/10.3390/w12051407

Samaniego, L., Thober, S., Kumar, R., Wanders, N., Rakovec, O., Pan, M., Zink, M., Sheffield, J., Wood, E. F., & Marx, A. (2018). Anthropogenic warming exacerbates European soil moisture droughts. *Nature Climate Change*, *8*(5), 421–426. https://doi.org/10.1038/s41558-018-0138-5

Scanlon, B. R., Faunt, C. C., Longuevergne, L., Reedy, R. C., Alley, W. M., Mcguire, V. L., & Mcmahon, P. B. (2012). Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley. *PNAS*, *109*(24). https://doi.org/10.1073/pnas.1200311109/-/DCSupplemental.www.pnas.org/cgi/doi/10.1073/pnas.1200311109

Schipper, E. L. F. (2020). Primer Maladaptation: When Adaptation to Climate Change Goes Very Wrong. *One Earth*, *3*(4), 409–414. https://doi.org/10.1016/j.oneear.2020.09.014

Shen, Y., Li, S., Chen, Y., Qi, Y., & Zhang, S. (2013). Estimation of regional irrigation water requirement and water supply risk in the arid region of Northwestern China 1989 – 2010. *Agricultural Water Management*, *128*, 55–64. https://doi.org/10.1016/j.agwat.2013.06.014

Soja, G., Züger, J., Knoflacher, M., Kinner, P., & Soja, A. (2013). Climate impacts on water balance of a shallow steppe lake in Eastern Austria. *Journal of Hydrology*, *480*, 115–124. https://doi.org/10.1016/j.jhydrol.2012.12.013

Soriano, E., Mediero, L., & Garijo, C. (2019). Selection of Bias Correction Methods to Assess the Impact of Climate Change on Flood Frequency Curves. *Water*.

Stein, U., Ö, G., Tr, J., Landgrebe, R., Szendrenyi, A., & Vidaurre, R. (2016). European Drought and Water Scarcity Policies. In *Governance for Drought Resilience. Land and Water Drought Management in Europe* (pp. 17–44). https://doi.org/10.1007/978-3-319-29671-5

Strosser, P., Dworak, T., Andrés, P., Delvaux, G., Berglund, M., Mysiak, J., Kossida, M., Iacovides, I., & Ashton, V. (2012). *Gap Analysis of the Water Scarcity and Droughts Policy in the EU European Commission*.

Sun, Y., Liu, N., Shang, J., & Zhang, J. (2017). Sustainable utilization of water resources in China : A system dynamics model. *Journal of Cleaner Production*, *142*, 613–625. https://doi.org/10.1016/j.jclepro.2016.07.110

Turral, H., Burke, J., Faures, J. M., & Faures, J. M. (2011). Climate change, water and food security. In *FAO Water Reports*. https://doi.org/ISSN 1020-1203

Valencia Cotera, R., Egerer, S., & Máñez Costa, M. (2022). Identifying Strengths and Obstacles to Climate Change Adaptation in the German Agricultural Sector : A Group Model Building Approach. *Sustainability*, *14*(4). https://doi.org/10.3390/su14042370

Wang, X., Zhang, J., & Ali, M. (2016). *Impact of climate change on regional irrigation water demand in Baojixia irrigation district of China*. 233–247. https://doi.org/10.1007/s11027-014-9594-z

Zhao, R., Liu, Y., Tian, M., Ding, M., Cao, L., Zhang, Z., Chuai, X., Xiao, L., & Yao, L. (2018). Impacts of water and land resources exploitation on agricultural carbon emissions: The water-land-energy-carbon nexus. *Land Use Policy*, *72*, 480–492. https://doi.org/10.1016/j.landusepol.2017.12.029

Zomorodian, M., Hin Lai, S., Homayounfar, M., Ibrahim, S., Ehsan Fatemi, S., & El-Shafie, A. (2018). *The state-of-the-art system dynamics application in integrated water resources modeling*. *227*(November 2017), 294–304. https://doi.org/10.1016/j.jenvman.2018.08.097

APPENDIX A: CLIMATE MODELS ENSEMBLES

Table 3.3. Model ensembles used for each RCP.

Regional Climate Model	Driver Model	Run type
CLMcom-CCLM4-8-17	CCCma-CanESM2	RCP 8.5
CLMcom-CCLM4-8-17	CNRM-CERFACS-CNRM-CM5	RCP 4.5
CLMcom-CCLM4-8-17	CNRM-CERFACS-CNRM-CM5	RCP 8.5
CLMcom-CCLM4-8-17	ICHEC-EC-EARTH	RCP 2.6
CLMcom-CCLM4-8-17	ICHEC-EC-EARTH	RCP 4.5
CLMcom-CCLM4-8-17	ICHEC-EC-EARTH	RCP 8.5
CLMcom-CCLM4-8-17	MIROC-MIROC5	RCP 8.5
CLMcom-CCLM4-8-17	MOHC-HadGEM2-ES	RCP 4.5
CLMcom-CCLM4-8-17	MOHC-HadGEM2-ES	RCP 8.5
CLMcom-CCLM4-8-17	MPI-M-MPI-ESM-LR	RCP 2.6
CLMcom-CCLM4-8-17	MPI-M-MPI-ESM-LR	RCP 4.5
CLMcom-CCLM4-8-17	MPI-M-MPI-ESM-LR	RCP 8.5
DMI-HIRHAM5	NCC-NorESM1-M	RCP 4.5
DMI-HIRHAM5	NCC-NorESM1-M	RCP 8.5
GERICS-REMO2015	ICHEC-EC-EARTH	RCP 2.6
GERICS-REMO2015	IPSL-IPSL-CM5A-MR	RCP 2.6
GERICS-REMO2015	MIROC-MIROC5	RCP 2.6
GERICS-REMO2015	MOHC-HadGEM2-ES	RCP 2.6
GERICS-REMO2015	MPI-M-MPI-ESM-LR	RCP 8.5
GERICS-REMO2015	NCC-NorESM1-M	RCP 2.6
GERICS-REMO2015	NCC-NorESM1-M	RCP 8.5
GERICS-REMO2015	NOAA-GFDL-ESM2G	RCP 2.6
IPSL-INERIS-WRF331F	IPSL-IPSL-CM5A-MR	RCP 4.5
IPSL-INERIS-WRF331F	IPSL-IPSL-CM5A-MR	RCP 8.5
KNMI-RACMO22E	CNRM-CERFACS-CNRM-CM5	RCP 4.5
KNMI-RACMO22E	CNRM-CERFACS-CNRM-CM5	RCP 8.5
KNMI-RACMO22E	ICHEC-EC-EARTH	RCP 2.6
KNMI-RACMO22E	ICHEC-EC-EARTH	RCP 4.5
KNMI-RACMO22E	ICHEC-EC-EARTH	RCP 8.5
KNMI-RACMO22E	IPSL-IPSL-CM5A-MR	RCP 8.5
KNMI-RACMO22E	MOHC-HadGEM2-ES	RCO 4.5
KNMI-RACMO22E	MOHC-HadGEM2-ES	RCO 8.5
KNMI-RACMO22E	MPI-M-MPI-ESM-LR	RCP 8.5
KNMI-RACMO22E	NCC-NorESM1-M	RCP 8.5
MPI-CSC	MPI-M-MPI-ESM-LR	RCP 2.6
MPI-CSC	MPI-M-MPI-ESM-LR	RCP 4.5
MPI-CSC	MPI-M-MPI-ESM-LR	RCP 8.5
SMHI-RCA4	CNRM-CERFACS-CNRM-CM5	RCP 4.5
SMHI-RCA4	CNRM-CERFACS-CNRM-CM5	RCP 8.5
SMHI-RCA4	ICHEC-EC-EARTH	RCP 2.6
SMHI-RCA4	ICHEC-EC-EARTH	RCP 4.5
SMHI-RCA4	ICHEC-EC-EARTH	RCP 8.5
SMHI-RCA4	IPSL-IPSL-CM5A-MR	RCP 4.5
SMHI-RCA4	IPSL-IPSL-CM5A-MR	RCP 8.5
SMHI-RCA4	MOHC-HadGEM2-ES	RCP 2.6
SMHI-RCA4	MOHC-HadGEM2-ES	RCP 4.5
SMHI-RCA4	MOHC-HadGEM2-ES	RCP 8.5
SMHI-RCA4	MPI-M-MPI-ESM-LR	RCP 2.6
SMHI-RCA4	MPI-M-MPI-ESM-LR	RCP 4.5
SMHI-RCA4	MPI-M-MPI-ESM-LR	RCP 8.5
UHOH-WRF361H	MPI-M-MPI-ESM-LR	RCP 8.5

APPENDIX B: MODEL DOCUMENTATION

Table 3.4. Model documentation.

Variable	Units	Description
Soil and aquifer dynamics, and irrigation demand		
Curve Number (CN)	Dmnl	*The Curve Number characterizes the runoff response of a drainage basin. The parameter reflects land use cover, land treatment, soil type, hydrological condition and previous soil moisture conditions.* **Value:** From 0 to 100 depending on the previously mentioned parameters. Value used in the model: 84.73 (after calibration) **References:** (Boonstra, 1994; Bos et al., 2009a)
S max retention	mm/month	*Represents infiltration after runoff has started. It is related to the soil properties represented by CN.* **Equation:** S = (25400/CN)-254 **Reference:** (Boonstra, 1994; Bos et al., 2009a)
Runoff	mm/month	*It represents the portion of water that does not infiltrate and it superficially drains from an area of land. According to the Curve Number Method, runoff only begins if precipitation is greater than 20% of S max retention.* **Equation:** IF THEN ELSE (Pp>(0.2*S max retention), ((Pp-(0.2*S max retention))^2)/(Pp+(0.8*S max retention)) , 0) **Reference:** (Boonstra, 1994; Bos et al., 2009a)
Precipitation (Pp)	mm/month	*Condensation of atmospheric water vapor.* **Value:** Historical records obtained from seven weather station in the region. Data provided by the Austrian Government. **Reference:** https://ehyd.gv.at/
Effective precipitation (Pe)	mm/month	*The fraction of precipitation useful for meeting the crop's water needs.*

		Equation: Pe = 0.8 P 25 if P > 75 mm/month; Pe = 0.6 P 10 if P < 75 mm/month **Reference:** (Brouwer & Heibloem, 1986)
Irrigation efficiency (n)	Dmnl	*Represents the irrigation efficiency of the implemented irrigation method. A higher efficiency means less water lost to evapotranspiration or runoff.* **Value:** Dependent on the irrigation method usually between 40 to 95% **Reference:** (Howell, 2003)
Crop factor (Kc)	Dmnl	*Represents the evapotranspiration of the grown crop compared to the reference crop ETo. It is used to determine the crops water needs. The value changes as the crop matures.* **Value:** Each crop has four crops depending on the growth stage. The values usually lay between 0.3 and 1.15. These values are found in manuals. **Reference:** (Brouwer & Heibloem, 1986)
Correction	Dmnl	*This parameter is included in the irrigation demand equation to give more room for calibration.* **Value:** 3.41 (after calibration)
Agricultural water	mm/month	*This parameter represents the irrigation water demand (IWD). It is calculated using the irrigation equation described in Chapter 3. The IWD is only calculated for the months when crops are irrigated (March until August). In the other months the Kc is set to zero and thus the IWD is also zero.* **Equation:** IF THEN ELSE((((Kc*ETr)-Pe)/(Correction*n))>=0, ((Kc*ETr)-Pe)/(Correction*n) , 0) **References:** (Brouwer & Heibloem, 1986; Shen et al., 2013; Wang et al., 2016)

Evapotranspiration (ETr)	mm/month	*Total water loss of water into the atmosphere from a surface.* **Value:** Calculated with the Community Water Model (CWatM) using the Penman-Monteith equation. **References:** (Burek et al., 2020; Monteith, 1965)
Infiltration	mm/month	*Portion of water entering the soil. It depends on the soil characteristics, the percentage of humidity in the soil and precipitation. In this case it was calculated as the product of precipitation minus runoff.* **Equation:** IF THEN ELSE(Pp-Runoff>0 , Pp-Runoff , 0)
Soil water	mm	*Fraction of water stored in the soil. Water enters through infiltration and leaves the stock either through recharge (when the S is reached) or through outflow (evapotranspiration).* **Equation:** Infiltration-Outflow-Recharge
Outflow	mm/month	*Fraction of soil humidity lost into the environment through evapotranspiration.* **Equation:** IF THEN ELSE((Soil water/TIME STEP)<=0, 0 ,IF THEN ELSE((Soil water/TIME STEP)<=ETr, (Soil water/TIME STEP)=ETr , ETr))
Recharge	mm/month	*Deep percolation. The fraction of water moving into the aquifer. In the model, deep percolation only happens after the S max retention is reached. In other words, when the soil can no longer store water.* **Equation:** IF THEN ELSE((Soil water/TIME STEP)>=S max retention, (Soil water/TIME STEP)-S max retention, 0)+ArtificialRecharge
Artificial recharge	mm/month	*Represents the project suggested by the government of Burgenland. We simulate a scenario where 3.75 M m^3/month (ca. 6.54 mm/month) will be diverted into Seewinkel and used to recharge the aquifer.*

		Value: 6.54 mm/month (3.75 M m3/month) **References:** (ORF, 2021).
Porosity	Dmnl	*The space between soil particles. The portion of soil volume where water can be stored. Dependent on soil particle size.* **Value:** 0.1897 (18.97%) (after calibration)
Groundwater	mm	*The volume of water stored in the underground in water permeable rock, rock fractures, or unconsolidated materials like silt, sand and gravel.* **Equation:** ((Recharge-Extraction-Base flow)/Porosity)
Extraction	mm/month	*Volume of water extracted from the aquifer for human use. For example for irrigation, drinking water and water for the industry.* **Equation:** Agricultural water*(Irrigated area/Total area)
Base flow	mm/month	*The volume of water discharged from the aquifer into surface waterbodies or flowing horizontally.* **Equation:** (Groundwater)*Recession time
Recession time	1/month	*The inverse of the time required for water to leave the aquifer.* **Value:** 0.013 (after calibration)

APPENDIX C: CROP FACTORS AND VEGETATION PERIODS

Table 3.5. Crop factors and days per growing stage for corn, potatoes and sugar beets according to Brouwer & Heibloem, (1986). Each crop has four crop factors for each of the four growth stages.

Crop Factor (Kc)				
Crop	**Initial stage**	**Crop development**	**Mid-season**	**Late season**
Corn	0.40	0.80	1.15	1.00
Potato	0.45	0.75	1.15	0.85
Sugar beet	0.45	0.80	1.15	0.80
Averaged	0.43	0.78	1.15	0.88
Vegetation Period				
Crop	**Initial stage**	**Crop development**	**Mid-season**	**Late season**
Corn	20-30 days	35-50 days	40-60 days	40-20 days
Potato	25-30 days	30-35 days	30-50 days	20-30 days
Sugar beet	25-45 days	35-65 days	60-80 days	40 days
Averaged	30 days	42 days	53 days	32 days

APPENDIX D: ADAPTATION SCENARIOS

Table 3.6. The fifteen simulations pairing each of the four adaptation measures to the three RCP scenarios.

Adaptation Scenario	RCP2.6	RCP4.5	RCP8.5
No changes implemented (BAU)	BAU_2.6	BAU_4.5	BAU_8.5
Shift to less water demanding crops (CROP)	CROP_2.6	CROP_4.5	CROP_8.5
Improved irrigation efficiency (IRRI)	IRRI_2.6	IRRI_4.5	IRRI_8.5
Artificial recharge (RECH)	RECH_2.6	RECH_4.5	RECH_8.5
Combined measures (COMB)	COMB_2.6	COMB_4.5	COMB_8.5

APPENDIX E: CROP FACTORS AND VEGETATION PERIODS OF A NEW CROP ROTATION

Table 3.7. Crop factors and days per growing stage for a new crop rotation consisting of less water demanding crops with shorter growing periods such as sorghum, barley, millet, soy or lentils according to Brouwer & Heibloem, (1986).

Crop Factor (Kc)				
Crop	Initial stage	Crop development	Mid-season	Late season
Averaged	0.35	0.73	1.12	0.65
Vegetation Period				
Crop	Initial stage	Crop development	Mid-season	Late season
Averaged	17 days	28 days	56 days	31 days

APPENDIX F: MODEL EQUATIONS

These equations compose the hydrological model developed in Chapter 3. To reproduce the hydrological model of Seewinkel, the equations can be directly copied and pasted into Vensim. To do this, open Vensim and click View>As Text. Once the visualization has changed, paste the equations. To view the model as stocks and flows, click View>As Sketch.

To run simulations, the model has to be fed with precipitation (Pp), evapotranspiration (ETr) and the crop factors (Kc) data. This data is stored in external files and fed to the model through either the "GET XLS DATA" function in Vensim or using the Python package "PySD". Because of this, in the equations, the values of Pp, ETr and Kc are given as 1.

However, the model should not be directly applied to a different region. The values of the constants shown in these equations, for example CN or porosity, were calibrated for Seewinkel. These values evidently will not apply in other regions. Because of this, before running any type of simulations for other regions, the model has to be calibrated.

```
Recharge=
	IF THEN ELSE((Soil water/TIME STEP)>=S max retention, (Soil water/TIME STEP)-S max retention\
		, 0 )+ArtificialRecharge
	~	mm/Month
	~	IF THEN ELSE((Soil water/TIME STEP)>=S max retention, (Soil water/TIME \
		STEP)-S max retention, 0 )+Artificial Recharge
	|

Agricultural water=
	IF THEN ELSE((((Kc*ETr)-Pe)/(Correction*n))>=0, ((Kc*ETr)-Pe)/(Correction*n) , 0 )
	~	mm/Month
	~		|

Groundwater= INTEG (
	((Recharge-Extraction-Base flow)/Porosity),
		416)
	~	mm
	~	Blaschke and Gschöpf (2011) mention that the aquifer has a thickness of 5 \
		to 20 m
	|

ArtificialRecharge=
	0
	~	 [0,6.54,0.02]
	~		|

Kc:INTERPOLATE::=
	1
	~	Dmnl
```

```
	~		|

Outflow=
	IF THEN ELSE((Soil water/TIME STEP)<=0, 0 ,IF THEN ELSE((Soil water/TIME STEP)<=ETr,\
		(Soil water/TIME STEP)=ETr , ETr )
	)
	~	mm/Month
	~		|

Pe=
	IF THEN ELSE(Pp>75, (0.8*Pp)-25 , (0.6*Pp)-10 )
	~
	~		|

Correction=
	3.01
	~
	~		|

Base flow=
	(Groundwater)*Recesion time
	~	mm/Month
	~		|

Extraction=
	Agricultural water*(Irrigated area/Total area)
	~	mm/Month
	~		|

Irrigated area=
	Total area*Irrigated percentage
	~
	~		|

Irrigated percentage=
	1
	~	[0,1,0.01]
	~		|

Total area=
	562
	~	km2
	~		|

Volume=
	Thickness+Groundwater
	~
	~		|
```

Thickness=
10128
~ m [0,150,1]
~ |

ActualET=
Outflow+(Agricultural water*0.35)
~ mm/Month
~ |

Limit=
-318
~ mm [-1000,1000,1]
~ |

Limit2=
-667.63
~ mm
~ |

Aquifer contribution=
0.00016
~ Dmnl
~ |

Aquifer contribution2=
0.4427
~ Dmnl
~ |

Aquifer contribution3=
0.9848
~ Dmnl
~ |

Out=
ETr+(Zicksee*Discharge)
~ mm/Month
~ ETr+(Zicksee*Discharge)
|

Out2=
ETr
~ mm/Month
~ ETp*(Lange Lacke*LostWater2)
|

```
Darscholacke= INTEG (
	In3-Out3,
		810)
	~	mm
	~		|

Out4=
	ETr+IF THEN ELSE(Illmitzer Zicksee>=Limit4, Discharge2*Illmitzer Zicksee , 0 )
	~	mm/Month
	~		|

Discharge2=
	0.2027
	~	1/Month
	~		|

ETr:INTERPOLATE::=
	1
	~	mm/Month
	~		|

Lange Lacke= INTEG (
	In2-Out2-To aquifer,
		710)
	~	mm
	~		|

In2=
	Pp+(Runoff*Runoff Fraction2)+(IF THEN ELSE(To aquifer>0, Aquifer contribution=0 , Aquifer
contribution\
		*ABS(Base flow) ))
	~	mm/Month
	~		|

In3=
	Pp+(Runoff*Runoff Fraction3)+(IF THEN ELSE(Groundwater<Limit2, Aquifer contribution2\
		=0 , ABS(Base flow)*Aquifer contribution2))
	~	mm/Month
	~		|

Runoff Fraction=
	0.298
	~	Dmnl [0,1,0.001]
	~		|

Runoff Fraction2=
	0.52
	~	Dmnl
```

```
	~		|

Illmitzer Zicksee= INTEG (
	In4-Out4,
		550)
	~	mm
	~		|

In=
	Pp+Artificial input+(Runoff*Runoff Fraction)
	~	mm/Month
	~		|

To aquifer=
	IF THEN ELSE(Groundwater<=Limit, Lange Lacke*Seepage coef , 0)
	~	mm/Month
	~	IF THEN ELSE(Groundwater<=Limit:AND:Lange Lacke<=Limit2, Lange \
		Lacke*Seepage , 0)
	|

Out3=
	ETr
	~	mm/Month
	~		|

In4=
	Pp+(Runoff*Runoff Fraction4)+(IF THEN ELSE(Groundwater<Limit3, Aquifer contribution3\
		=0 , ABS(Base flow)*Aquifer contribution3))
	~	mm/Month
	~		|

Limit4=
	345.53
	~	mm
	~		|

Runoff Fraction3=
	0.4638
	~	Dmnl
	~		|

Runoff Fraction4=
	0.9805
	~	Dmnl
	~		|

Seepage coef=
	0.02
```

~ 1/Month [0,0.5,0.001]
~ |

Limit3=
-645.12
~ mm
~ |

Artificial input:INTERPOLATE::=
20.54
~ mm/Month [0,1000]
~ 300,000 m3/year. Lake area is 121.7 ha so 300,000m3/121.7ha*year = \
246.5mm/year (20.54 mm/month). In 2010 the allowed water input was reduced \
from 2,1 Mm3 (143.8 mm/month) to only 300,000 m3/year. In 2011 there was a \
human error and 562,000m3 were pumped in so in 2010 only 38,000 m3 were \
left.
|

Discharge=
0.0202
~ 1/Month [0,1,0.001]
~ LostWater
|

n=
1
~ Dmnl [0,1,0.01]
~ Irrigation Efficiency Howell Table 1 - Moving big gun n = 65
|

Zicksee= INTEG (
In-Out,
900)
~ mm
~ St. Adrä Zicksee
|

Infiltration=
IF THEN ELSE(Pp-Runoff>0 , Pp-Runoff , 0)
~ mm/Month
~ |

Water Balance=
Pp-Runoff-Infiltration
~ mm/Month
~ |

Runoff=

```
	IF THEN ELSE (Pp>(0.2*S max retention), ((Pp-(0.2*S max retention))^2)/(Pp+(0.8*S max
retention
)) , 0 )
	~	mm/Month
	~		|

CN=
	84.73
	~	Dmnl [0,100,1]
	~	Curve Number Table 4.2 Row Crops Soil A or B
	|

Recesion time=
	0.013
	~	1/Month [1e-06,0.1,0.0001]
	~	1/recession time
	|

Porosity=
	0.1897
	~	Dmnl [0,1,0.01]
	~		|

Pp:INTERPOLATE::=
	1
	~	mm/Month
	~		|

S max retention=
	(25400/CN)-254
	~	mm/Month
	~		|

Soil water= INTEG (
	 Infiltration-Outflow-Recharge,
		160)
	~	mm
	~		|

********************************************************
	.Control
********************************************************~
		Simulation Control Parameters
	|

FINAL TIME  = 1139
	~	Month
	~	The final time for the simulation.
```

|

INITIAL TIME = 0
~ Month
~ The initial time for the simulation.
|

SAVEPER =
TIME STEP
~ Month [0,?]
~ The frequency with which output is stored.
|

TIME STEP = 1
~ Month [0,?]
~ The time step for the simulation.
|

CHAPTER 4: *An Assessment of Water Management-Based Climate Change Adaptation in Lower Saxony.*

An Assessment of Water Management-Based Climate Change Adaptation in Lower Saxony

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KEYWORDS
System dynamics, climate change adaptation, water management, agriculture, Lower Saxony.

RESEARCH QUESTIONS

- How efficient are adaptation measures to reduce water demand?
- What is the most effective adaptation measure suggested by stakeholders and why?
- What is the effect of Net-Zero trends on emissions compared to the current emissions trend?

ABSTRACT
Climate change has increased the intensity, frequency and duration of heatwaves and droughts in Europe turning water management into an even more complicated issue. Because water is a fundamental resource for agriculture, water management has to be addressed with climate change adaptation. While local stakeholders are aware of adaptation measures they could implement to dampen the effects of climate change, evidence of the effectiveness of adaptation measures at a local scale is still missing. An analysis of adaptation measures using a new hydrological model was performed to test four adaptation measures suggested by stakeholders. Changing crops has the strongest effect followed by improving irrigation efficiency, humification and lastly artificial aquifer recharge. If crops are changed, irrigation water demand and energy consumption could be reduced by up to 20.7%, costs could be reduced in 19.1%, the aquifer level could rise up to 284.85 mm, and emissions could be reduced by 26.6% by the end of the century. Artificial recharge proved to be an inadequate method for the region as it does not affect the irrigation water demand and an insufficient amount of water is available to have a substantial effect on the aquifer.

4.1. INTRODUCTION

Water is a fundamental resource for food production and life. Around 12% of the global ice-free surface is used for agriculture; with 10% covered by rain-fed agriculture and 2% by irrigated agriculture (IPCC, 2019). While irrigated agriculture only covers a relatively small fraction of the Earth's crust, it provides 40% of the global food supply (Turral et al., 2011). This makes irrigation essential to ensure food security. Since 1961 irrigation water demand has been continuously increasing and the irrigation water volume has now more than doubled (IPCC, 2019). Currently, irrigated agriculture is responsible for 70% of the global fresh water extractions (Chen et al., 2016; FAO, 2014).

In Europe, agriculture covers 40% of the land and approximately 6% of that land is irrigated at least once a year (EEA, 2019). European agriculture accounts for 25% of the Union's water extractions (EEA, 2019) with the bigger users of irrigation water being Spain and Italy with 16.7 and 11.7 billion m3 per year (Rossi, 2019). In some countries, water extractions for irrigation have already reduced the quality of aquifers with Cyprus, Hungary, Spain, Greece, Malta, Italy and France having the most aquifers affected by agricultural water extractions (EEA, 2021). It is expected that agricultural water demand will continue to increase due to climate change. Because of the strong relationship between agriculture and water, an adequate management of water resources is therefore crucial to ensure food security for the future.

Moreover, droughts are becoming a new challenge in Central Europe. In most parts of Central Europe, including Germany, drought frequency has increased since the 1950s (EEA, 2020) and since the beginning of the 21st century, an increase of heatwaves and droughts has been observed with noticeable events in 2003, 2018 and 2019 (Ionita, 2020). Drought events can lead to severe economic losses. The drought of 2003 for example, caused losses of €1.5 billion in the agricultural sector alone (Zink et al., 2016). Climate change is expected to exacerbate heat related events such as heat waves and droughts (Ionita, 2020; IPCC, 2019). This means that droughts events will set in faster, last longer and be more intense (Samaniego et al., 2018)

Climate change is turning water management for agriculture into a more complicated issue. Therefore, climate change adaptation will be required to deal with the new climatic conditions (Iglesias & Garrote, 2015). Adapting to climate change is especially important for agriculture to ensure food security (EEA, 2019). In the case of irrigation-dependent agriculture, a useful method to promote adaptation is through water management. Traditionally, there are two approaches to water management: increasing water supply and managing water demand (Correia de Araujo et al., 2019). Measures used to reduce the amount of water necessary to achieve a goal are known as water demand management (WDM) (Wang et al., 2016).

WDM can trigger changes in agricultural systems; however, some of these changes imply trade-offs. For example, increasing water pricing or imposing water restrictions can force changes in crop rotation (Sapino et al., 2022) but these changes can also cause declines in the region's net benefits from agriculture (Mitter & Schmid, 2021) and yield reduction (Sapino et al., 2022). Reducing the farmers' income could lead to rebounding maladaptation. Rebounding maladaptation refers to measures that increase the vulnerability of the targeted or implementing actor (Juhola et al., 2016).

Because of this, understanding how multiple individuals' decisions interact and aggregate is crucial to determining how water will be allocated between multiple users (Cravens et al., 2021).

Modern irrigation methods consume considerable amounts of energy (Flammini et al., 2014). Consequently, optimization of irrigation could lead to significant energy savings (European Commission, 2015) thereby indirect emissions generated during the electricity production. Following the goals of the EU, Germany opted to reach a reduction of 80 to 95% in the GHG emissions by 2050 (BMU, 2016). The target date was later updated to 2045 (BMUV, 2021). This commitment is known as the Net-Zero initiative. Agriculture is one of the five sectors bound to reduce its emissions. For this reason, considering energy consumption in the agricultural climate change adaptation process should be a priority. Adaptation measures, which increase energy and water use, should be avoided, as increasing the consumption of resources would result in maladaptation.

Prior to this analysis, we engaged local stakeholders using a participatory modeling approach to assess their perceptions on climate change and identify if adaptation measures were being implemented (Valencia Cotera, Egerer, et al., 2022). Twenty local stakeholders, including farmers and decision makers, were interviewed and engaged in a Group Model Building (GMB) process (Vennix, 1996). Previous studies have shown the advantages of participatory modeling processes for climate change adaptation (Gómez Martín et al., 2020; Máñez Costa et al., 2017; Williams, 2020). During the GMB process, we compiled a series of adaptation measures mentioned by stakeholders. The measures where then qualitatively assessed using a leverage point analysis (Egerer et al., 2021). However, the majority of these measures have not been quantitatively analyzed or implemented yet. We find this to be a knowledge gap in the region‘s climate change adaptation, as evidence of the outcome, efficiency and systemic effect of implementing adaptation measures is still missing.

To bridge this gap, we developed a hydrological impact model in System Dynamics (SD) to test the effectiveness of adaptation measures (Valencia Cotera, Guillaumot, et al., 2022). The SD model was originally developed and used to perform an impact assessment for Seewinkel, an important agricultural region in East Austria. In this work, the model has been adapted and re-calibrated for the county of Uelzen, Germany, with historical hydrological and climate data. We tested the effect of several adaptation measures on the dynamic behavior of the system under three Representative Concentration Pathways (RCP) scenarios. The SD model runs with future climate projections provided by the World Climate Research program EURO-CORDEX initiative (Jacob et al., 2014) for three RCPs (RCP 2.6, 4.5, and 8.6).

There is extensive evidence suggesting that the willingness of farmers to adapt to climate change is significantly influenced by their climate change perceptions and awareness (Abid et al., 2019; Aidoo et al., 2021; Jha & Gupta, 2021). Education and access to weather and climate information significantly influenced their climate change perceptions (Jha & Gupta, 2021; Li et al., 2021; Nyang’au et al., 2021). Therefore, providing climate information to farmers and other decision makers is a crucial step to influence their climate change perceptions and promote adaptation (Brosch, 2021; Maltby et al., 2021). Based on this, we believe that local farmers and decision makers could benefit greatly from the results of our impact model analyses. By promoting science-based decision-making, we aim to reduce the local risk of implementing measures, which could lead to maladaptation.

Under this framework, this study seeks to support climate change adaptation by providing information regarding the effectiveness of adaptation measures. The goal of our analysis is to model changes in the system's behavior after the implementation of adaptation measures to anticipate ineffective practices and possible maladaptive effects. The analysis is done under two emissions scenarios. First, the current emission trend, which will reach carbon neutrality around the year 2064. Second, the Net-Zero initiative, in which carbon neutrality is reached in 2050. With this, we wish to determine: (I) How effective are adaptation measures to reduce water demand and preserve the aquifer? (II) How do adaptation measures reduce energy, costs and emissions? (III) Is there a significant effect of Net-Zero trends on emissions savings compared to the current emissions trend?

4.2. CASE STUDY

This study focuses on the county of Uelzen; an important agricultural district in Lower Saxony, Germany (Figure 4.1). More specifically, Uelzen is located in North East Lower Saxony (NELS) and it is part of the largest irrigated area in Germany (Egerer et al., 2021). In NELS (10,731 km2) 47% of the land is used for agriculture (Umweltbundesamt, 2018). The region is of particular interest, as farmers focus on the cultivation of essential crops such as potatoes, sugar beets, corn, and grains. These crops in turn, support the local production of sugar, starch and biogas. The latter is subsequently used to produce electricity and district heating.

NELS is characterized by its sandy soils. Because of this, the intensive land use is mainly possible due to field irrigation, as it compensates for the low summer precipitation and the low water storage capacity of the soil (Grocholl et al., 2014). Since the second half of the 20th century, farmers made a high investment in irrigation systems to secure high yields (LWK Niedersachsen, 2012). Farmers chose gun-cart irrigation systems as they found it required less work than other irrigation methods and it was efficient enough. Around 90% of the water used for irrigation is extracted from aquifers (Wittenberg, 2015). Historically, water availability and the cost of water was not an issue for farmers in Uelzen.

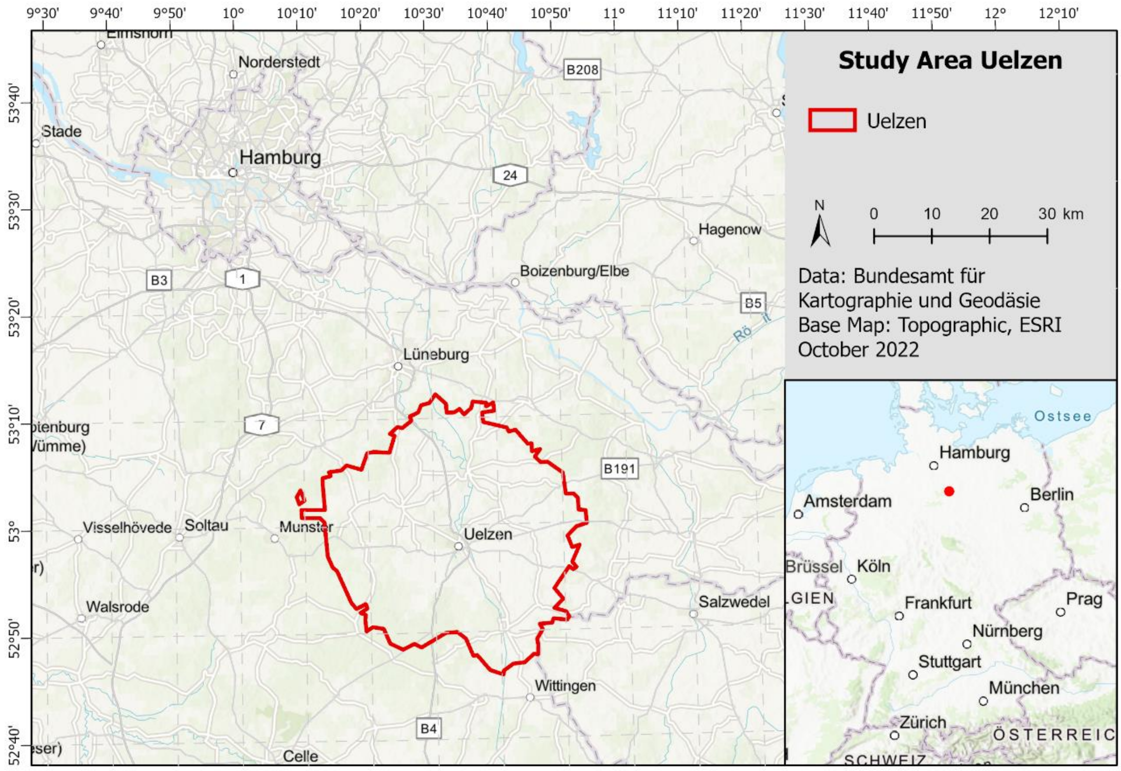

Figure 4.1. Location of Uelzen in Germany

Climate change is expected to affect precipitation patterns in NELS. As to the extent of this change, models show no conclusive trends yet. The models, however, do show a tendency for precipitation to decrease during the summer months and increase during spring, autumn and winter (Rechid et al., 2014; Scheihing, 2019). Related to this, an increase in the total amount of yearly precipitation has been recorded, with an increase in 8mm per decade for the period 1897-2007 (Grocholl et al., 2014). This increase in mean annual precipitation can be explained by the intensification of winter precipitation.

However, it should be kept in mind that a change in rain patterns could cause a reduction in groundwater recharge and an increase in the soil water deficit during the summer months (Bender et al., 2017). Because of this, it would be wise to consider and expect that irrigation demand, and therefore groundwater extraction, can increase under climate change conditions (Bender et al., 2017; Schulz & Wendland, 2014). In addition to this, extreme weather events, such as drought and heatwaves, could also further increase irrigation demand. Such was the case of the drought of 2018 in Germany. The lack of precipitation and increased temperatures led to a drastic increase in groundwater demand for irrigation. As a result, more than 30% of the groundwater monitoring stations in NELS surpassed their historical recorded low points (Wriedt, 2019).

4.3. RESEARCH METHOD

4.3.1 System Modelling

System thinking is helpful method to understand behaviors, predict them and subsequently adjust their outcomes (Arnold & Wade, 2015). Because of this, implementing systems thinking modelling, like for example System Dynamics, is a useful method to design more effective policies (Sterman, 2000). In the case of climate change adaptation, impact models based on system thinking can be developed to test adaptation strategies and understand their effect on the entire system. This is particularly beneficial as, at a local scale, evidence of the efficiency of climate change adaptation measures is usually lacking. Additionally, a simulation of management strategies must be ideally done before any strategies are implemented (Bala et al., 2017). System's thinking theory has been used for assessing the effectiveness of Nature-Based Solutions (Gómez Martín et al., 2021), groundwater management (Arasteh & Farjami, 2021), evaluation of climate change adaptation strategies for water resource management (Gohari et al., 2017), and drought-oriented water management of rivers (Rubio-Martin et al., 2020). Under this framework, we have decided to implement system modelling to simulate the region's behavior under climate change and test the effect of adaptation measures on the system.

4.3.2 Climate Projection Data

This study uses EURO-CORDEX data (Jacob et al., 2014) and considers three RCP scenarios: RCP 2.6, RCP 4.5 and RCP 8.5. First presented in the Fifth Assessment Report (AR5) of the IPCC, the RCP scenarios represent three possible climate change futures. These future projections are dependent on the amount of carbon emission that will be emitted in the upcoming decades. A multi-model ensemble was used for each RCP scenario (Appendix G). The model was run with each ensemble and afterwards the average of the outputs was taken as a result. Monthly near-surface temperature (tas) and precipitation (pr) were directly taken from the ensemble members. Potential evapotranspiration (evaspsblpot) was calculated based on daily tas and maximum and minimum near-surface temperature (tasmax and tasmin) using the method by Hargreaves & Samani, (1985) included in the python package xclim (Logan et al., 2021). Afterwards, spatial averages over Uelzen were calculated using the pyweights function.

Climate model outputs however, are biased from observations by inaccuracies in conceptualization, discretization, spatial averaging within grid cells (Soriano et al., 2019) limited representation of local features, incorrect boundary conditions and parametrization (Pastén-Zapata et al., 2020). The main source of uncertainty, however, are the driving global climate models (GCM) (Senatore et al., 2022). Therefore, it is not recommended to use climate data directly as input for impact models, as regional climate models (RCMs) may still have considerable systematic biases that could produce inaccurate results (Mendez et al., 2020; Pastén-Zapata et al., 2020). In most climate change impact studies, bias correction methods are used to improve the RCM data's statistical properties so they are more comparable to observed ones (Galmarini et al., 2019; Mendez et al., 2020). With bias correction methods, climate model projections are corrected using the model bias calculated against observations (Senatore et al., 2022).

In the case of water resources research, it is still necessary to apply bias correction before the data is used due to the climate models' bias (Fang et al., 2015). By applying bias correction methods large errors are expected to be removed thus increasing the confidence on hydrological models (Tumsa, 2022). Hydrological models using bias corrected data produce results with a reduced simulation spread, thus making them more useful for impact assessments (Pastén-Zapata et al., 2020). Therefore, in this study, the climate data was bias adjusted before feeding the hydrological impact model to avoid producing results with a high spread.

In this study the data correction was performed by applying the standard deviation method proposed by Bouwer et al. (2004) (Equation 1). The advantages of this method are its ability to correct the climate model's mean values as well as properly correcting extreme values. Additionally, the simplicity of this method makes it an advantageous option, as it does not require complicated calculations or high computational power. By applying this method, the climate data is corrected against the observed average and also for the observed variance. In this case, the model was calibrated using ERA5 data. The climate data was corrected against ERA5 to keep consistency with the calibration. The chosen baseline period is 1978 – 2005.

(1) $$a'_{cm,j} = \frac{(a_{cm,j} - \bar{a}_{cm,j})}{\sigma_{cm,j}} \times \sigma_{obs,j} + \bar{a}_{obs,j}$$

In Eq. 1, a'cm,j is the corrected climate parameter of a particular month "j". acm,j is the uncorrected simulated climate parameter. ācm,j is the average simulated climate parameter over the baseline period. σcm,j is the standard deviation of the simulated parameter over the baseline period. σobs,j is the standard deviation of the observed climate parameter over the baseline period and āobs,j is the average observed climate parameter over the baseline period.

4.3.3 The Impact Model

The quantitative model is composed of two sections: a hydrological sub-model and an energy-cost-emissions sub-model. The hydrological sub-model has been previously developed and tested in a similar agricultural region in Austria (Valencia Cotera, Guillaumot, et al., 2022). The energy-emissions sub-model was developed exclusively for the Uelzen region, as stakeholders emphasized the strong relationship between irrigation systems and energy consumption. The energy sub-model calculates the energy required to irrigate using aquifer water. Energy use implies that farmers have to cover the costs of energy and that their energy use attributes the CO2 emissions of energy production to them.

Because of the large influence of irrigation on the regional hydrology, the model includes an irrigation demand equation (Agricultural water on Figure 4.2). This equation calculates the irrigation water demand (IWD) of the region based on evapotranspiration, precipitation, a crop factor dependent on the planted crops, the efficiency of the irrigation method and the total irrigated area. By adding the irrigation demand to the drinking water and industry water demand, the model calculates the total water extracted from the aquifer on a monthly basis.

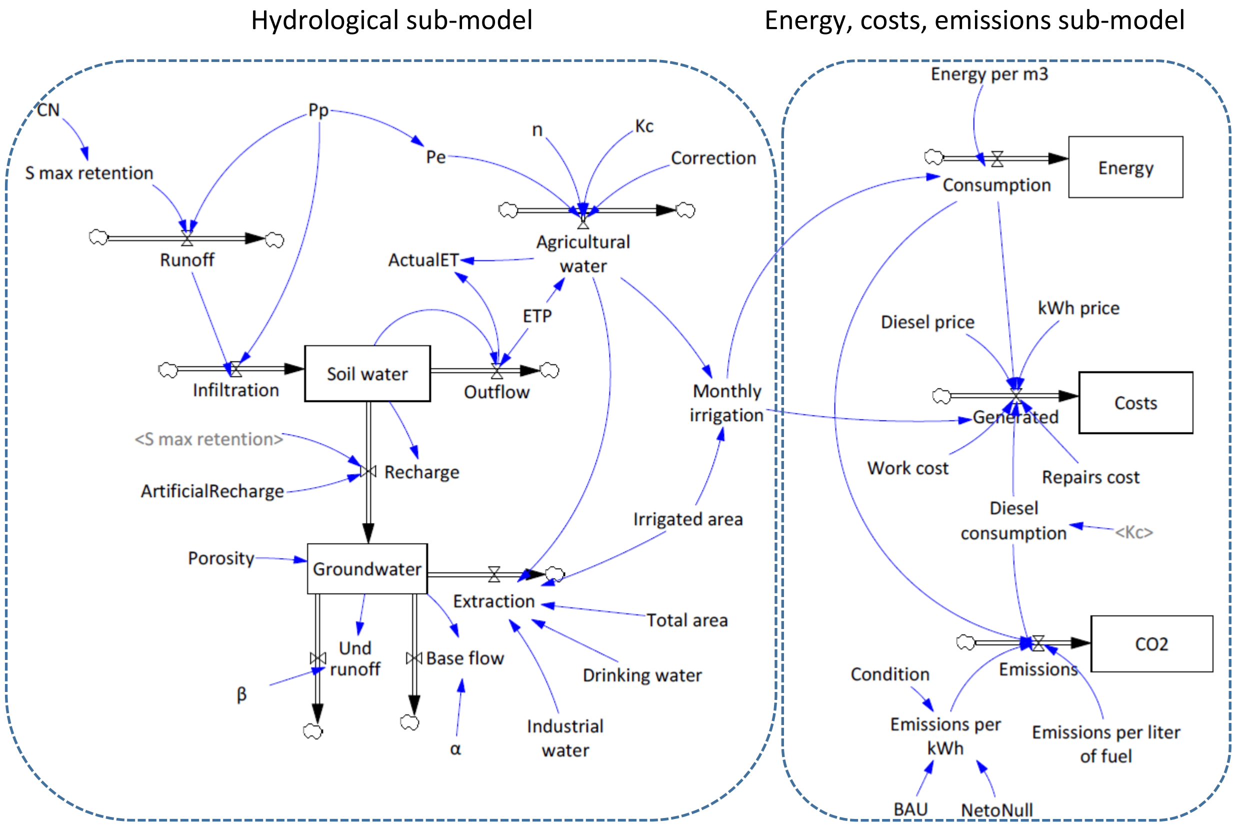

Figure 4.2. The SD model including the hydrological sub-model on the left and the energy, costs, emissions sub-model on the right. A detailed description of the model's elements can be found in the model documentation in Appendix I.

4.3.4 Description and development of the hydrological sub-model

The hydrological sub-model (left panel in Figure 4.2) runs using climate data of the region; more specifically, precipitation (Pp) and evapotranspiration (ETP). It consists of two stocks, one representing the water stored in the upper layers of the soil (Soil water in Figure 4.2) and one representing the water stored in the aquifer (Groundwater in Figure 4.2). The model also includes an irrigation equation to simulate agricultural water demand for irrigation (Agricultural water in Figure 4.2).

The soil water has an inflow and two outflows. Precipitation water is stored in the soil and leaves through evapotranspiration. However, when the maximum water retention capacity of the soil is reached water moves from the soil into the aquifer as recharge water (Recharge in Figure 4.2). The soil characteristics and the amount of runoff produced after precipitation are calculated using the curve number method (Bos et al., 2009a).

The aquifer has a water inflow (Recharge in Figure 4.2) and three outflows (Extraction, Underground runoff and Base flow in Figure 4.2). The amount of extracted water is determined by the total water demand of agriculture, drinking water, and the industrial use. Water also moves out of the aquifer through underground runoff and baseflow. Underground runoff feeds the local rivers, like the Ilmenau. The base flow simulates the water leaving the aquifer in other directions rather than the river. This flow is calibrated using the recession flow parameter.

4.3.5 Irrigation equation

To consider the IWD, we adapted the irrigation equation presented by Wang et al. (2016) (Equation 1). This equation approximates irrigation water demand based on evapotranspiration and usable precipitation. The irrigation equation is the second driver of the model after the climate data (*Pp* and *ETP*). By adding such an equation, we seek to approximate and simulate the future irrigation-water demand based on climate conditions.

(1) $$IN = ETc - Pe + \Delta W + G$$

Where *IN* is the irrigation water (mm), *ETc* is the reference crop evapotranspiration (mm), *Pe* is the effective precipitation (mm), *ΔW* is the soil water storage capacity (mm), and lastly *G* is the ground water recharge during the period (mm). To simplify the process *IN* is taken as the difference between *ETc* and *Pp* (Equation 2).

(2) $$IN = ETc - Pp$$

The reference crop evapotranspiration (ETc) is defined as the multiplication of a crop factor (Kc) and the crop evapotranspiration (ETo). Because in our case, the model uses the potential evapotranspiration as an input, we chose to use that value instead of a reference value (Equation 3).

(3) $$ETc = Kc * ETP$$

Substituting equation 3 in equation 2 yields:

(4) $$IN = (Kc * ETP) - Pp$$

IN values are only used if they are equal or greater than zero. Negative values refer to months in which the precipitation was greater than the evapotranspiration therefore they are discarded and substituted by a zero.

As mentioned earlier, the region is specialized in growing three crops: potatoes, sugar beets and corn. However, data is not available to determine exactly how many hectares of each crop are planted each season. Because of this, lack of available information forced us to approximate *Kc* and the days per growing stage to a single value, which could closely represent the behavior of the three crops. The calculation of these factors is based on the information presented by Brouwer & Heibloem (1986) (Appendix J).

Finally, the total irrigation water requirement (IWR) is calculated based on Shen et al. (2013) by taking all the previous factors into account, plus the total agricultural area and the irrigation efficiency (Equation 5). *S* is the total agricultural area (km2), *IN* is the previously calculated irrigation water (mm) and *n* is the efficiency of the irrigation method implemented (%).

(5) $$IWR = \frac{S * IN}{n}$$

Equation 5 was validated by comparing it to irrigation data of Uelzen (Appendix K). In this case, the formula required a correction factor (cf) which resulted in the final formula (Equation 6) to be as follows:

(6) $$IWR = \frac{S * IN}{n * cf}$$

4.3.6 Description and development of the energy-costs-emissions sub-model

In Germany, the emissions produced by electricity generation have been declining since 1990 (Umweltbundesamt, 2014). If this trend continues to decrease, emissions from electricity production would reach zero around the year 2064. However, if measures are implemented to achieve the goals of the German Climate Action Plan 2050, emissions should reach zero in 2050. These two emissions trends are considered in the energy-costs-emissions sub-model (BAU and NettoNull in Figure 4.2) to calculate the emissions per kWh consumed.

The energy-costs-emissions sub-model (right panel in Figure 4.2) uses historical data to calculate the approximate energy needed per cubic meter of irrigation water. This energy expended is then translated into costs (in Euros) and into emissions (Kg of CO2 per kWh). The costs for electricity are based on a fixed price of 0.3 €/kWh. The emissions per kWh are calculated based on the average emissions for current national electricity mix trend in Germany and the Net-Zero scenario.

The sub-model also includes other factors such as diesel consumption, work cost of irrigation and costs of irrigation equipment repairs to calculate the costs and emissions per km^2. These values are based on historical averages. The model does not calculate the emissions produced directly by agriculture activities such as fertilizer use, as the goal of the study is to simulate energy use under climate change.

4.3.7 Model calibration

The model was calibrated using normalized observational data for the aquifer and ERA 5 data (Hersbach et al., 2020) for Pp and ETP. The aquifer data includes information from more than 55 groundwater-monitoring stations in the county of Uelzen. The data was provided by the Lower Saxony Department for Water, Coastal and Nature Conservation (NLWKN). A long reference period (1978 – 2018) was used to reduce uncertainty.

The model has five parameters, which need to be calibrated. The five parameters are: curve number (CN), irrigation efficiency (n), porosity (p), recession time (α), and underground runoff coefficient (β) (Figure 4.2). The optimization function of Vensim was used to calibrate these parameters. The built-in optimization function of Vensim allows the user to select the variables to optimize the model. The software then runs the model several times and compares the model output to the observed data. After this, the software suggests values for the selected variables.

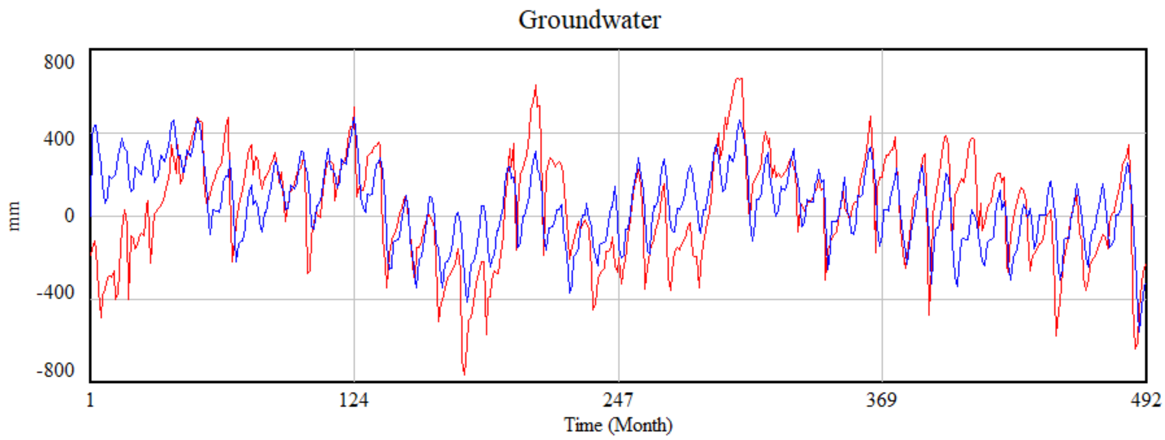

Figure 4.3. Comparison between observation data for the aquifer depth (in red) and the model (in blue). The reference period of 492 months starts in January 1978 and ends on December 2018.

A goodness-of-fit analysis was performed after the calibration. In hydrology, the coefficient of determination (R^2) is the standard metric to test the goodness-of-fit between observations and simulations. R^2 indicates correlation but it does not quantify the model bias and it can be low for an accurate model and high for an inaccurate model (Onyutha, 2022). Because of this, two additional coefficients were considered: the Nash-Sutcliffe efficiency (NSE) (Nash & Sutcliffe, 1970) and the Kling-Gupta Efficiency (KGE) (Gupta et al., 2009).

The Nash-Sutcliffe efficiency (NSE) measures the relative magnitude between the residual variance and the measured data variance (Moriasi et al., 2015). A NSE = 1 indicates that the model output perfectly matches the observations, NSE < 0 indicates that the model is a worse predictor than the mean of observations, and NSE = 0 is usually used as the threshold to distinguish between a satisfactory and an unsatisfactory model (Knoben et al., 2019). More specifically NSE values of: <0.2; 0.2-0.4; 0.4-0.6; 0.6-0.8; and >0.8 are classified as: insufficient; sufficient; good; very good; and excellent, respectively (Okiria et al., 2022). Others set the limit for a satisfactory model at NSE > 0.5 (Moriasi et al., 2007).

The KGE is based on an equal weighting of bias, correlation and variability measures and when used for model calibration it considerably improves the bias and the variability and only slightly decreases the correlation (Gupta et al., 2009). The KGE has been increasingly used for model evaluation and calibration as it was developed to address some shortcomings in NSE (Knoben et al., 2019). For KGE, values below zero are considered an unsatisfactory model, while 0.5 > KGE > 0 is considered a poor performing model (Knoben et al., 2019). It is important to emphasize that KGE and NSE cannot be compared directly and they should not be seen as equivalents (Knoben et al., 2019).

After calibration the model achieved an R^2 = 0.48, a NSE = 0.48 and a KGE = 0.78 when comparing the historical data of the aquifer to the simulations. While this performance can be deemed as acceptable, there are several possible shortcomings in the model and in the data that do not allow for a higher model fit. First, the model is a lumped model without spatial distribution; therefore, it has reduced accuracy. Second, there are strong variations in several of the measuring stations, with considerable drops in the water level during the growing season. A possible reason for this being well drawdown caused by water extractions too close to the measuring point. Thirdly, the area of the county of Uelzen might be too large (1,454 km^2). However, because this is an impact model, this study has a higher interest in understanding trends and behaviors rather than presenting high precision hydrological modelling information.

4.3.8 Simulating adaptation measures

The adaptation scenarios are based on adaptation measures suggested by stakeholders and recorded after a previously implemented Group Model Building process (Valencia Cotera, Egerer, et al., 2022). That study identified that some of the most mentioned adaptation measures were: (I) Reusing and storing water; (II) Humification to increase the soil quality; (III) Digitalization and precision agriculture; and (IV) New crop rotation. Based on this, five adaptation scenarios were developed and simulated. These scenarios are first, a scenario where no adaptation measures are implemented (BAU). Second, a scenario where a fraction of the grey water is used to recharge the aquifer (ARC). This grey water is produced after urban water (drinking and industry water) is treated. Third, a scenario where humification is promoted at a large scale (HUM). Fourth, a scenario where precision agriculture increases the efficiency of irrigation (PIR). Fifth, a change to a new crop rotation with less water demanding crops (CRP).

Parameters in the model were changed to simulate the large-scale implementation of these adaptation measures. In the BAU scenario the model ran without changes to simulate the current conditions. In the ARC scenario, 50% percent of the water extracted for drinking water and irrigation was used to artificially recharge the aquifer. This was preferred over building storage ponds, because they require high initial investments and large areas. To counteract these disadvantages the aquifer can be used as a natural reservoir. In the HUM scenario, CN was reduced by 1.04 x 10^3 per month to simulate a gradual increase in humus content resulting in a reduction of one in the CN by the end of the century. Because humus retains humidity, it decreases the need for irrigation. Therefore, cf was also adjusted accordingly. In the PIR scenario, irrigation efficiency was increased to 85% to simulate a change from gun-cart irrigation systems to lateral movement irrigation. Finally, in the CRP scenario the Kc was changed to simulate a large-scale implementation of a crop rotation with less water demanding crops (Appendix J).

Because adaptation is not an immediate process, the model considers the time required to implement the adaptation measures. Humification, for example, is a process that requires decades to complete. Therefore, the HUM scenario begins in 2023 and it gradually changes CN and cf until 2100. Improving the irrigation method is a costly process that not all farmers can immediately implement. To simulate a slow transition from the current irrigation methods to more efficient ones, in the PIR scenario, n begins to increase in 2023 and ends in 2035. In the same manner, changing the crop rotation is a slow and complex process. In the CRP scenario, Kc starts to change in 2023 and it ends in 2035 to simulate a slow transition to a new crop rotation. The ARC scenario, however, begins in 2023 as the implementation of an artificial recharge project could be done in less than a year.

SD software, like Vensim, limits the input data to one data set. This means that the software can perform only one simulation at the time. This is a severe limitation for impact models using climate data, as usually simulations are performed using climate data ensembles. In order to overcome this limitation, the Python library PySD was used to run and feed the model. The PySD library was developed specifically to facilitate the integration of data science and Vensim models (Houghton & Siegel, 2015).

4.4 RESULTS

This section presents the dynamic behavior of the system under three climate change scenarios. By focusing on the behavior of the system, it is possible to determine the systemic effect of implementing the suggested adaptation measures. The adaptation measures are compared to the BAU scenario, which is used as a baseline. To compare and rank the effectiveness and viability of the different adaptation measures, this study focuses on the long-term trends of the irrigation demand, the aquifer, and the energy consumption, costs and emissions.

4.4.1 Irrigation water demand under climate change and adaptation scenarios.

For all three RCPs, the CRP adaptation scenario is the most efficient in reducing IWD followed by PIR and HUM (Figure 4.4). The ARC scenario has no effect on the IWD as it only affects the aquifer but it does not influence neither the decisions taken by farmers nor the crops' water requirements. The average IWD for the BAU scenario across all RCPs is 8.15 mm/month. This value is reduced to 6.46 mm/month in the CRP scenario, to 6.91 mm/month in the PIR scenario and to 7.54 mm/month in the HUM scenario. This means that, when compared to BAU across all RCPs, the CRP scenario reduces IWD by an average of 20.7%, PIR reduces it by 15.2% and HUM reduces it by 7.5%.

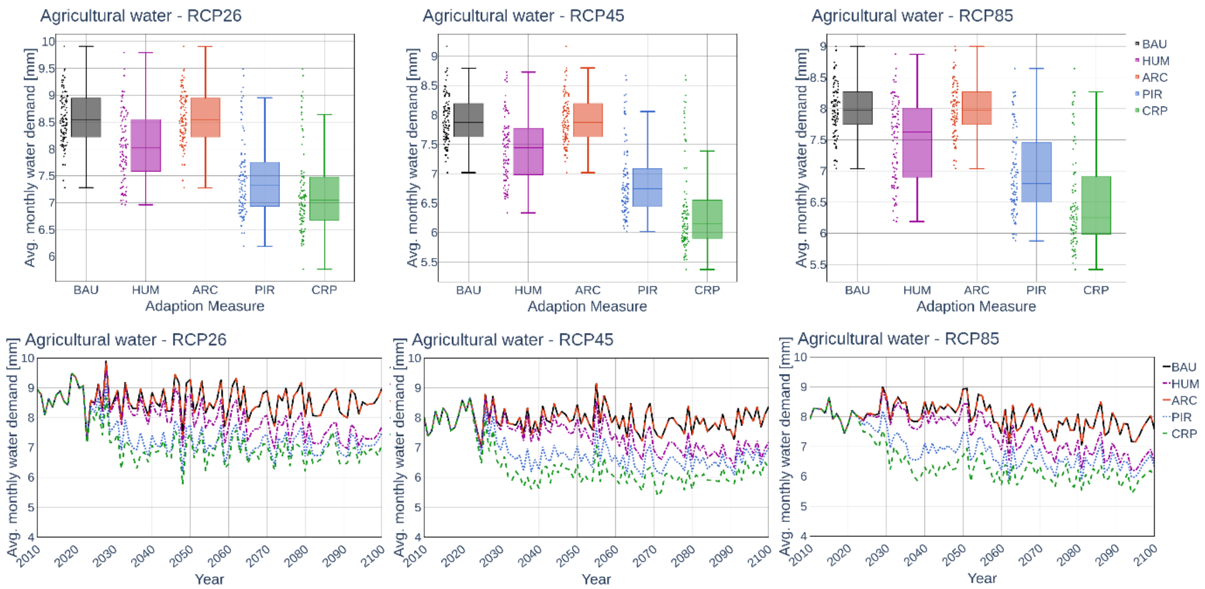

Figure 4.4. The effect of the four adaptation measures on the IWD in Uelzen compared to the BAU baseline for three climate change scenarios.

4.4.2 Aquifer dynamics under climate change and adaptation scenarios.

The CRP adaptation scenario is again the most effective to increase the groundwater level for all RCPs followed by PIR, then HUM and lastly by ARC (Figure 4.5). When compared to BAU across all RCPs, in the CRP scenario the groundwater level increases by an average of 240.85 mm, in the PIR scenario it increases it by 177.05 mm, in the HUM scenario it increases it by 118.03 mm and in the ARC scenario it increases it by only 3.15 mm. The highest increase in groundwater level happens in RCP 8.5 and the lowest increase in the RCP 2.6 scenario.

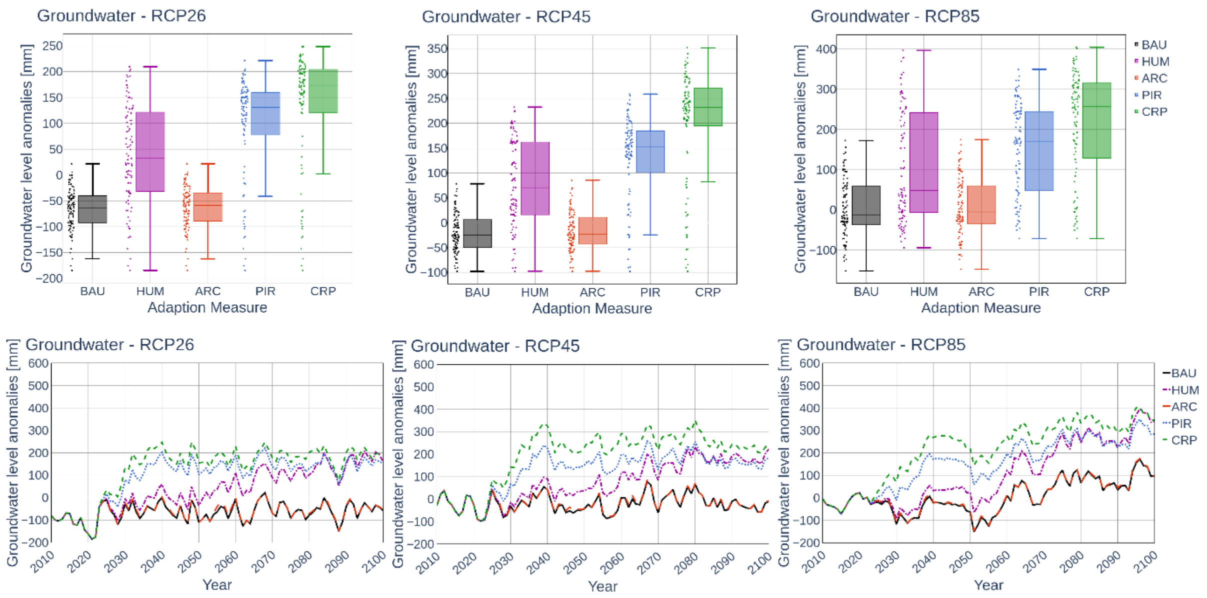

Figure 4.5. The effect of the four adaptation measures on the groundwater in Uelzen compared to the BAU baseline for three climate change scenarios.

4.4.3 Energy, costs and emissions under climate change and adaptation scenarios.

Regarding the irrigation energy demand in Uelzen during the 21st century, the adaptation scenarios have again the same order of effect as with the IWD (Figure 4.6). The average monthly energy consumption for the BAU scenario across all RCPs is 48.9 kWh/ha. The CRP scenario would reduce the energy demand to 38.8 kWh/ha. PIR would reduce the energy demand to 41.5 kWh/ha. HUM would reduce the energy demand to 45.2 kWh/ha. ARC would not have any effect as it only influences the volume of available water but it does not affect IWD. This means that CRP could reduce the energy demand by 20.7%, PIR by 15.2% and HUM by 7.5%.

The reduction in energy consumption corresponds to a similar reduction in GHG emissions. Under the current trend and when compared to BAU, CRP would produce 15.3% less emissions, PIR could produce 3.8% less and HUM almost 1% less by the end of the century. However, if actions are implemented to reach Net Zero in 2050, CRP could avoid 26.7% less emissions. While PIR and HUM could avoid up to 16.1% and 14.6% respectively.

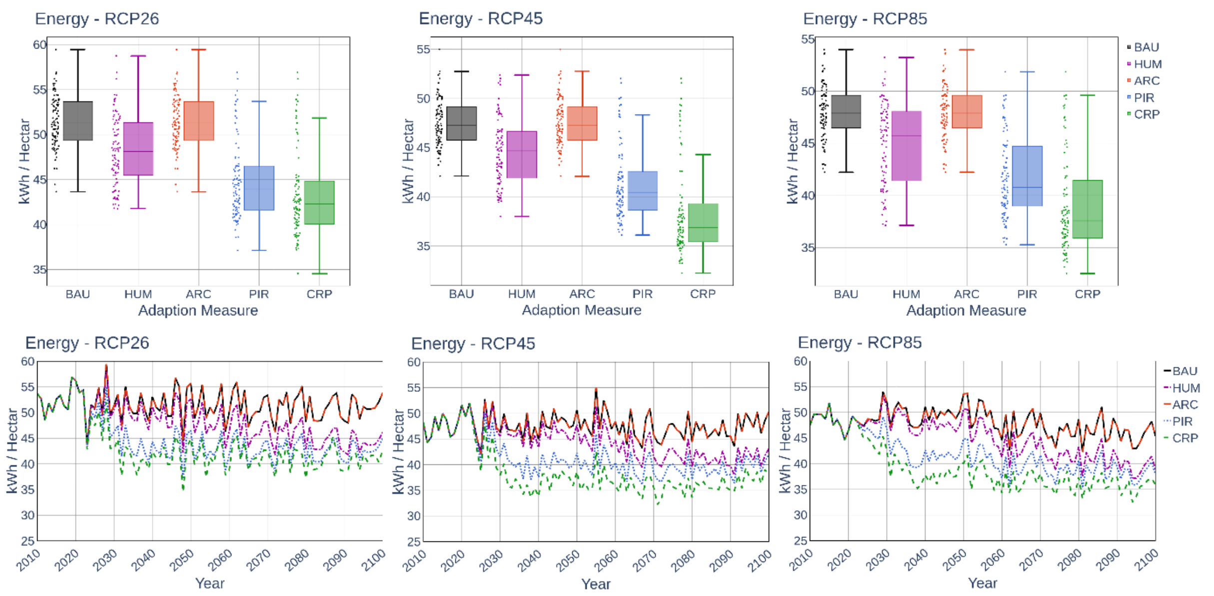

Figure 4.6. The effect of the four adaptation measures on the energy demand of agriculture in Uelzen compared to the BAU baseline for three climate change scenarios.

Energy and costs are closely linked, as energy is the highest cost of irrigation. Therefore, by decreasing irrigation, farmers are saving energy and reducing their operational costs (Figure 4.7). The average monthly energy costs for the BAU scenario across all RCPs is 23.3 €/ha. The CRP scenario would reduce the energy costs per hectare to 18.8 €/ha by the end of the century. PIR would reduce the energy costs to 20.6 €/ha and HUM would reduce them to 21.9 €/ha. ARC has no effect on the IWD, therefore it also does not affect the costs. They represent reductions in cost of 19.1%, 11.4% and 5.7%, accordingly.

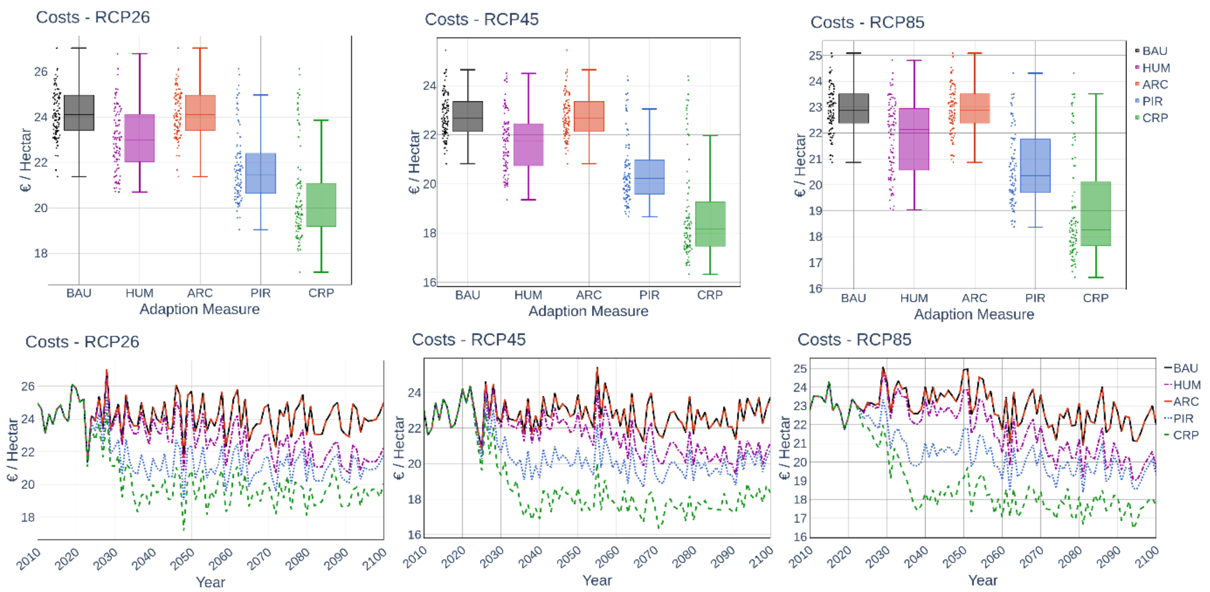

Figure 4.7. The effect of the four adaptation measures on the costs to agriculture in Uelzen compared to the BAU baseline for three climate change scenarios

4.5. DISCUSSION

4.5.1 Effectiveness, benefits and trade-offs of the adaptation measures.

The results of this study show that, under all RCPs, the most efficient adaptation measure to reduce IWD and therefore energy, costs and emissions is a change to less water-demanding crops. The CRP scenario is followed by an investment in precision agriculture to increase the irrigation efficiency and lastly, a shift in agricultural practices to promote humification. The same order of effectiveness applies to the aquifer. However, in this case, artificially recharging the aquifer with treated water does have an effect. The effect is negligible in comparison to the other measures, as the water volume extracted for drinking water and the industry is considerably smaller in comparison to the water volume extracted by agriculture.

Changing and diversifying crops is the most effective measure, as on average, it helps reduce the IWD by 20.7% by the end of the century. This in turn has positive effects on the aquifer as, on average, it increases its level by 240.85 mm by the end of the century when compared to the BAU. Because irrigation is linked to energy use and emissions, decreasing irrigation through CRP causes a reduction in costs of 23.3 €/ha (BAU) to 18.8 €/ha, a reduction of energy use of 20.7% and considerable cuts in emission. In the current emissions trend, CRP could avoid 15.3% less emissions by the end of the century and 26.7% less under the Net-Zero trend. The drastic cuts in emissions and IWD could be explained by the lower Kc of the new crop rotation but also because this crop rotation is shorter, thus it requires fewer inputs; for example less water. Our results go in line with other studies, which have also confirmed that changing crops can reduce energy demands and thus CO_2 emissions (Canaj & Mehmeti, 2022; Mohammadi et al., 2014; Rathore et al., 2022). While changing and diversifying crops to create a shift into less water-demanding crops might have a considerable effect on the IWD of the region, achieving this in Uelzen might be extremely difficult in reality. The agriculture industry in Uelzen is entirely based on the cultivation of these crops because of their high economic value; this in turn creates a reinforcing feedback loop (Egerer et al., 2021). This can cause a high resistance to change due to the chances of economic losses caused by a shift to a new crop rotation (Valencia Cotera, Egerer, et al., 2022). However, opting for a new crop rotation as an adaptation strategy can have additional benefits such as: improving yields (Farina et al., 2008; Huynh et al., 2019; Teixeira et al., 2017), increasing the soil biota (Torppa & Taylor, 2022; Zhang et al., 2021), increasing soil organic carbon, and nitrogen content (Zhang et al., 2021), increasing the plant nitrogen uptake and intrinsic water use efficiency (Bowles et al., 2022) and increasing yields even under drought conditions (Bowles et al., 2020). Therefore, designing a new crop rotation for Uelzen would not only be beneficial for the local water resources, and to help cut down emissions, but it could promote that farms shift to more favorable practices.

Irrigation is one of the most important factors affecting yields in Uelzen. In dry years, irrigation can almost double the yields in comparison to rainfed agriculture (Huynh et al., 2019). Our results show that, because irrigation has such a strong effect on the local groundwater, increasing irrigation efficiency would bring a multitude of benefits such as protection of local water resources, reduced emissions, and a reduction in operational costs. By implementing PIR, the IWD could be reduced by an average of 15.2% and the aquifer level could increase an average of 177.05 mm by the end of the century for all RCP scenarios when compared to the BAU. This means that farmers could still rely on irrigation to secure their yields, while at the same time promote an increase in the groundwater level. However, the shift to more efficient irrigation methods requires a high initial investment which farmers are generally not ready to make unless incentives are granted (Pilarova et al., 2022). Therefore subsidizing more efficient irrigation systems can promote their adoption and implementation (Heumesser et al., 2012; Issaka et al., 2018). Our results have also shown that a reluctance to change the irrigation method would increase the costs per hectare, as in the PIR scenario the costs per hectare were, on average, 11.4% lower for all RCPs and when compared to the BAU scenario. This could be a crucial difference to keep farms operational and financially sustainable during drought periods. A similar benefit was observed for the emissions as in the PIR scenario, 3.8% less CO_2 could be emitted under the current trend and 16.1% less under the Net-Zero trend. Our results are in line with other studies, which have already shown that irrigation methods should be improved to promote energy efficiency and reduce carbon emissions (Jamali et al., 2021; Khoshnevisan et al., 2013; Zhao et al., 2018).

The results have also shown that changing agricultural practices to promote humification can have a positive influence to reduce IWD and preserve the aquifer. This is because humus conservation and improvement has beneficial effects on soil structure, water-holding capacity and plant nutrient supply (Piccolo, 1996). More specifically, higher organic matter contents resulting in higher soil water contents (Bordoloi et al., 2019; De Jong et al., 1983). Because of this, by promoting humification, the IWD could be reduced by an average of 7.51% for all RCPs. This in turn would imply an average reduction in costs of 23.3 €/ha to 21.9 €/ha, an average reduction of energy use of 7.51% and considerable cuts in emission. In the current emissions trend, HUM could avoid the emission of 1% less CO_2 by the end of the century and 14.6% less CO2 under the Net-Zero trend when compared to the BAU. Moreover, soil organic matter promotes good soil structure, increases water infiltration and reduces soil erosion (Bot & Benites, 2005). This can be confirmed by our results as humification has also positive effects on the aquifer. On average, humification promotes an increase of 118.03 mm in the aquifer levels by the end of the century when compared to the BAU. Increasing the soil organic content has additional benefits from which farmers could profit. Supplementing soils with humus-rich compost can increase nutrient content in the soil (Lord & Sakrabani, 2019) and promote shoot and root growth, nutrient uptake and mycorrhizal colonization (Solaiman et al., 2019). Usually no-till farming is suggested to promote humification as intensive tillage may damage soil properties and degrade soil. However, it has been proved that no tillage can negatively affect yields; at least during the first years (Camarotto et al., 2018; Huynh et al., 2019). Finally, it should be taken into account that humification is a slow process happening over several decades and it might imply changes to the crop rotation.

Finally, the least effective adaptation measure is the reuse of drinking and industrial water. This adaptation measure has three main downsides. First, the amount of water extracted for drinking and industrial use is too small in comparison to the water extracted for irrigation. Therefore, even when 50% of that water is treated and returned to the aquifer, the effect is almost negligible. If implemented, the aquifer would only increase its level an average of 3.15 mm for all RCPs by the end of the century. Second, because this measure only affects the aquifer it does not have any effect on the IWD and therefore it also does not reduce energy, costs, and emissions caused by the reliance on agriculture. Third, artificial recharge has potential risks to aquifer water quality as recharge water disinfection could lead to the generation of disinfection by-products (Chai et al., 2022), untreated water could introduce pathogens (Page et al., 2010) and polluted water could introduce chemical pollutants (Yu et al., 2022). Additionally, current wastewater treatments fail to completely remove drugs, micro- and nano-plastics, hormones, antibiotic resistance germs and bacteria, contaminants of emerging concern and personal care products among others (Valhondo et al., 2020). Therefore, recharge with treated water could pose additional risks, as it could be a vector for other pollutants. However, solutions like treatment barriers (Page et al., 2010), reactive barriers (Valhondo et al., 2020), and disinfection and colloid supplement (Chai et al., 2022) have been implemented to deal with pollutants in aquifer recharge water. Because of the ineffectiveness of water reuse to reduce IWD and increase the aquifer level, building additional water storage ponds in Uelzen could be equally futile.

4.5.2 Importance of Net-Zero.

Our study has shown the relevance and importance of implementing actions to reach the goals of the German Climate Action Plan 2050. While decarbonizing electricity is a challenging process, a 100% renewable-based system for electricity is feasible in Germany (Maruf, 2021). Solar and wind energy are currently the main pillars of renewable energy in Germany and it is expected that they will become the major source of energy in the next decades (Dotzauer et al., 2022). Decarbonizing electricity by 2050 would assist many sectors, including agriculture, to reduce their indirect emissions through energy consumption. Our results show that in the case of Uelzen, the Net-Zero trend has a substantial effect in avoiding emissions when compared to the current trend. On average, 26.7% less CO_2 could be emitted in the CRP scenario, 16.1% less CO_2 in the PIR scenario and 14.6% less CO_2 in the HUM scenario compared to BAU in the current emissions trend. This means that no matter which adaptation measure would implemented, the Net-Zero trend would always have substantial emissions savings over the current trend. Additionally, these savings could be much larger if two or more adaptation measures would be implemented at the same time, as their combined effects on the system would induce higher energy savings.

4.5.3 Limitations and further research.

While this study has given a general overview of the systemic effects that adaptation could have in Uelzen, there are certain limitations that need to be addressed. First, this study is not looking at yearly spikes caused by drought events. This means that while the adaptation measures might be useful in the long run, this study does not show how effective they are to buffer the effects of climate extremes. Second, because the model lacks an agricultural sub-model, it does not model the yields. Therefore, it does not calculate the profits generated. With the profits and the costs available, an assessment could be performed to determine if farms would become unprofitable under climate change.

To bridge the limitations of this study, we propose that further research could focus on climate extremes and their effects on the region. By focusing on climate extremes and doing a similar analysis to the one presented here, it should be possible to determine which adaptation measures could help mitigate the effects of seasonal droughts. Furthermore, further research could develop an agricultural sub-model to simulate the effect that climate adaptation could have on yields. By doing this, it should be possible to better understand the positive economic effects that adaptation could have.

4.6. CONCLUSION

We have implemented an impact assessment of climate change adaptation measures in Uelzen using an impact model under three Representative Concentration Pathways (RCP) scenarios. We have concluded that changing crops is the most efficient way to adapt to climate change, followed by increasing irrigation efficiency, promotion of humus formation and lastly artificial recharge of the aquifer. Implementing a new crop rotation, increasing the irrigation efficiency and promoting humus formations would significantly reduce IWD and reduce costs and emissions. Artificially recharging the aquifer has almost unperceivable effects on the aquifer level and it does not affect neither the IWD nor the costs and emissions.

The results have also highlighted the importance of achieving the objectives of the German Climate Action Plan 2050. While adaptation measures should be implemented at a farm level, decision makers should also promote and accelerate the shift to clean electricity. If a shift to renewable energy is achieved by 2050, adaptation of agriculture could also have a mitigating effect. Our results have shown that if proper measures are implemented to decarbonize electricity, a portion of the emissions caused by energy demand in agriculture could be avoided. This is another example of the indirect benefits of climate change adaptation at a systemic level.

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AUTHOR CONTRIBUTIONS

Methodology, R.V.C.; investigation, R.V.C. and S.E.; formal analysis, R.V.C.; software, R.V.C and L.M; writing—original draft preparation, R.V.C.; writing—review and editing, S.E. C.N., L.L., L.M. and M.M.C; supervision, M.M.C.; funding acquisition, M.M.C. All authors have read and agreed to the published version of the manuscript.

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REFERENCES

Abid, M., Scheffran, J., Schneider, U. A., & Elahi, E. (2019). Farmer Perceptions of Climate Change, Observed Trends and Adaptation of Agriculture in Pakistan. *Environmental Management*, *63*(1), 110–123. https://doi.org/10.1007/s00267-018-1113-7

Aidoo, D. C., Boateng, S. D., Freeman, C. K., & Anaglo, J. N. (2021). Heliyon The effect of smallholder maize farmers ' perceptions of climate change on their adaptation strategies : the case of two agro-ecological zones in Ghana. *Heliyon*, *7*(April), e08307. https://doi.org/10.1016/j.heliyon.2021.e08307

Arasteh, M. A., & Farjami, Y. (2021). New hydro-economic system dynamics and agent-based modeling for sustainable urban groundwater management : A case study of Dehno , Yazd. *Sustainable Cities and Society*, *72*(June), 103078. https://doi.org/10.1016/j.scs.2021.103078

Bala, B. K., Arshad, F. M., & Noh, K. M. (2017). *System Dynamics*.

Bender, S., Butts, M., Hagemann, S., Smith, M., Vereecken, H., & Wendland, F. (2017). *Der Einfluss des Klimawandels auf die terrestrischen Wassersysteme in Deutschland*. https://www.climate-service-center.de/products_and_publications/publications/detail/064955/index.php.de

BMU. (2016). *Klimaschutzplan 2050 - Klimaschutzpolitische Grundsätze und Ziele der Bundesregierung*.

BMUV. (2021). *Lesefassung des Bundes-Klimaschutzgesetzes 2021 mit markierten Änderungen zur Fassung von 2019*. https://www.bmuv.de/fileadmin/Daten_BMU/Download_PDF/Klimaschutz/ksg_aendg_2021_3_bf.pdf

Boonstra, J. (1994). Estimating Peak Runoff Rates. In *The Handbook of Applied Hydrology* (pp. 121–144). McGraw Hill New York.

Bordoloi, R., Das, B., Yam, G., Pandey, P. K., & Prakash, O. (2019). Modeling of Water Holding Capacity Using Readily Available Soil Characteristics. *Agricultural Research*, *8*(3), 347–355. https://doi.org/10.1007/s40003-018-0376-9

Bos, M. G., Kselik, R. A. L., Allen, R. G., & Molden, D. J. (2009a). Effective Precipitation. In *Water Requirements for Irrigation and the Environment* (pp. 81–101). Springer. https://doi.org/https://doi.org/10.1007/978-1-4020-8948-0

Bos, M. G., Kselik, R. A. L., Allen, R. G., & Molden, D. J. (2009b). Irrigation Water Requirements 5.1. In *Water Requirements for Irrigation and the Environment*. Springer Netherlands. https://doi.org/https://doi.org/10.1007/978-1-4020-8948-0

Bot, A., & Benites, J. (2005). The importance of soil organic matter. Key to drought-resistant soil and sustained food production. In *FAO Soils Bulletin 80*. FAO. https://doi.org/10.5194/soil-1-707-2015

Bouwer, L. M., Aerts, J. C. J. H., Coterlet, G. M. van der, Giesen, N. van de, Gieske, A., & Mannaerts, C. (2004). Evaluating Downscaling Methods for Preparing Global Circulation Model (GCM) Data for Hydrological Impact Modelling. In J. Aerts & P. Droogers (Eds.), *Climate Change in Contrasting River Basins* (pp. 25–47).

Bowles, T. M., Jilling, A., Mor, K., & Grandy, A. S. (2022). *Crop rotational complexity affects plant-soil nitrogen cycling during water deficit*. *166*. https://doi.org/10.1016/j.soilbio.2022.108552

Bowles, T. M., Mooshammer, M., Socolar, Y., Schmer, M. R., Strock, J., & Grandy, A. S. (2020). Long-Term Evidence Shows that Crop-Rotation Diversification Increases Agricultural Resilience to Adverse Growing Conditions in North America. *ONe Earth*, *2*, 284–293. https://doi.org/10.1016/j.oneear.2020.02.007

Brosch, T. (2021). Affect and emotions as drivers of climate change perception and action : a review. *COBEHA*, *42*, 15–21. https://doi.org/10.1016/j.cobeha.2021.02.001

Brouwer, C., & Heibloem, M. (1986). *Irrigation Water Management: Irrigation Water Needs. Training Manual no. 3*. FAO.

Burek, P., Satoh, Y., Kahil, T., Tang, T., Greve, P., Smilovic, M., & Guillaumot, L. (2020). Development of the Community Water Model (CWatM v1 . 04) – a high-resolution hydrological model for global and regional assessment of integrated water resources management. *Geoscientific Model Development*, *13*, 3267–3298.

Camarotto, C., Dal Ferro, N., Piccoli, I., Polese, R., Furlan, L., Chiarini, F., & Morari, F. (2018). Conservation agriculture and cover crop practices to regulate water, carbon and nitrogen cycles in the low-lying Venetian plain. *Catena*, *167*(May), 236–249. https://doi.org/10.1016/j.catena.2018.05.006

Canaj, K., & Mehmeti, A. (2022). Analyzing the water-energy-environment nexus of irrigated wheat and maize production in Albania. *Energy Nexus*, *7*(May), 100100. https://doi.org/10.1016/j.nexus.2022.100100

Chai, J., Zhang, W., Liu, D., Li, S., Chen, X., & Yang, Y. (2022). Decreased levels and ecological risks of disinfection by-product chloroform in a field-scale artificial groundwater recharge project by colloid supplement. *Environment International*, *161*, 107130. https://doi.org/10.1016/j.envint.2022.107130

Chen, J., Shi, H., Sivakumar, B., & Peart, M. R. (2016). Population, water, food, energy and dams. *Renewable and Sustainable Energy Reviews*, *56*, 18–28. https://doi.org/10.1016/j.rser.2015.11.043

Correia de Araujo, W., Oliveira Esquerre, K. P., & Sahin, O. (2019). Building a System Dynamics Model to Support Water Management : A Case Study of the Semiarid Region in the Brazilian Northeast. *Water*, *11*.

Cravens, A. E., Henderson, J., Friedman, J., Burkardt, N., Cooper, A. E., Haigh, T., Hayes, M., Mcevoy, J., Paladino, S., Wilke, A. K., & Wilmer, H. (2021). A typology of drought decision making: Synthesizing across cases to understand drought preparedness and response actions. *Weather and Climate Extremes*, *33*(July), 100362. https://doi.org/10.1016/j.wace.2021.100362

De Jong, R., Campbell, C. A., & Nicholaichuk, W. (1983). Water retention equation and their relationship to soil organic matter and particle size distribution for disturbed samples. *Canadian Journal of Soil Science*, *63*, 291–302.

Dotzauer, M., Oehmichen, K., Thär, D., & Weber, C. (2022). Empirical greenhouse gas assessment for fl exible bioenergy in interaction with the German power sector. *Renewable Energy*, *181*. https://doi.org/10.1016/j.renene.2021.09.094

EEA. (2019). *Climate change adaptation in the agriculture sector in Europe*. *04/2019*.

EEA. (2020). *Meteorological and hydrological droughts in Europe*. eea.europa.eu

EEA. (2021). *Water and agriculture: towards sustainable solutions*. Publications Office of the European Union. https://doi.org/10.2800/73735

Egerer, S., Valencia-Cotera, R., Celliers, L., & Máñez Costa, M. (2021). A leverage points analysis of a

qualitative system dynamics model for climate change adaptation in agriculture. *Agricultural Systems*, *189*(January). https://doi.org/10.1016/j.agsy.2021.103052
European Commission. (2015). *Energy use in the EU food sector : State of play and opportunities for improvement*. https://doi.org/10.2790/158316
Fang, G. H., Yang, J., Chen, Y. N., & Zammit, C. (2015). Comparing bias correction methods in downscaling meteorological variables for a hydrologic impact study in an arid area in China. *Hydrology and Earth System Sciences*, *19*, 2547–2559. https://doi.org/10.5194/hess-19-2547-2015
FAO. (2014). *The Water-Energy-Food Nexus. A new approach in support of food security and sustainable agriculture.*
Farina, R., Bene, C. Di, Piccini, C., Marchetti, A., Troccoli, A., & Francaviglia, R. (2008). Do Crop Rotations Improve the Adaptation of Agricultural Systems to Climate Change ? A Modeling Approach to Predict the Effect of Durum Wheat-Based Rotations on Soil Organic Carbon and Nitrogen. In *Soil Management and Climate Change* (pp. 221–236). Elsevier Inc. https://doi.org/10.1016/B978-0-12-812128-3.00015-X
Flammini, A., Puri, M., Pluschke, L., & Dubois, O. (2014). *Walking the Nexus Talk : Assessing the Water-Energy-Food Nexus in the Context of the Sustainable Energy for All Initiative*. FAO.
Galmarini, S., Cannon, A. J., Ceglar, A., Christensen, O. B., Noblet-ducoudré, N. De, Dentener, F., Doblas-Reyes, F. J., Dosio, A., Gutierrez, J. M., Iturbide, M., Jury, M., Lange, S., Loukos, H., Maiorano, A., Maraun, D., McGinnis, S., Nikulin, G., Riccio, A., Sanchez, E., … Zampieri, M. (2019). Adjusting climate model bias for agricultural impact assessment : How to cut the mustard. *Climate Services*, *13*, 65–69. https://doi.org/10.1016/j.cliser.2019.01.004
Gohari, A., Mirchi, A., & Madani, K. (2017). System Dynamics Evaluation of Climate Change Adaptation Strategies for Water Resources Management in Central Iran. *Water Resources Management*. https://doi.org/10.1007/s11269-017-1575-z
Gómez Martín, E., Giordano, R., Pagano, A., van der Keur, P., & Máñez Costa, M. (2020). Using a system thinking approach to assess the contribution of nature based solutions to sustainable development goals. *Science of the Total Environment*, *738*, 139693. https://doi.org/10.1016/j.scitotenv.2020.139693
Gómez Martín, E., Máñez Costa, M., Egerer, S., & Schneider, U. A. (2021). Assessing the long-term effectiveness of Nature-Based Solutions under different climate change scenarios. *Science of the Total Environment*, *794*. https://doi.org/10.1016/j.scitotenv.2021.148515
Grocholl, J., Mersch, I., Rechid, D., & Urban, B. (2014). Charakteristika des Modellgebietes Lüneburger Heide. In *Klimawandel in der LÜNEBURGER HEIDE – Kulturlandschaften zukunftsfähig gestalten* (pp. 5–10).
Gupta, H. V, Kling, H., Yilmaz, K. K., & Martinez, G. F. (2009). Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling. *Journal of Hydrology*, *377*(1–2), 80–91. https://doi.org/10.1016/j.jhydrol.2009.08.003
Hargreaves, G. H., & Samani, Z. A. (1985). Reference Crop Evapotranspiration from Temperature. *Applied Engineering in Agriculture*, *1*(2), 96–99. https://doi.org/10.13031/2013.26773
Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., … Thépaut, J. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, *146*(730), 1999–2049. https://doi.org/10.1002/qj.3803
Heumesser, C., Fuss, S., Szolgayová, J., Strauss, F., & Schmid, E. (2012). Investment in Irrigation Systems under Precipitation Uncertainty. *Water Resources Management*, *26*(11), 3113–3137. https://doi.org/10.1007/s11269-012-0053-x
Houghton, J., & Siegel, M. (2015). A dvanced data analytics for system dynamics models using PySD. *Proceedings of the 33rd International Conference of the System Dynamics Society.*
Howell, T. A. (2003). Irrigation Efficiency. In *Encyclopedia of Water Science*. Marcel Dekker, Inc. https://doi.org/10.1081/E-EWS 120010252

Huynh, H. T., Hufnagel, J., Wurbs, A., & Bellingrath-kimura, S. D. (2019). Field Crops Research In fl uences of soil tillage , irrigation and crop rotation on maize biomass yield in a 9-year fi eld study in Müncheberg , Germany. *Field Crops Research*, *241*(July), 107565. https://doi.org/10.1016/j.fcr.2019.107565

Iglesias, A., & Garrote, L. (2015). Adaptation strategies for agricultural water management under climate change in Europe. *Agricultural Water Management*, *155*, 113–124. https://doi.org/10.1016/j.agwat.2015.03.014

Ionita, M. (2020). On the curious case of the recent decade , mid-spring precipitation de fi cit in central Europe. *Npj Climate and Atmospheric Science*, 1–10. https://doi.org/10.1038/s41612-020-00153-8

IPCC. (2019). Climate Change and Land. In *An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*.

Issaka, Z., Li, H., Yue, J., Tang, P., & Darko, R. O. (2018). Water-smart sprinkler irrigation , prerequisite to climate change adaptation : a review. *Journal of Water and Climate Change*, 383–398. https://doi.org/10.2166/wcc.2018.017

Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O. B., Bouwer, L. M., Braun, A., Colette, A., Déqué, M., Georgievski, G., Georgopoulou, E., Gobiet, A., Menut, L., Nikulin, G., Haensler, A., Hempelmann, N., Jones, C., Keuler, K., Kovats, S., … Yiou, P. (2014). EURO-CORDEX: new high-resolution climate change projections for European impact research. *Regional Environmental Change*, *14*(2), 563–578. https://doi.org/10.1007/s10113-013-0499-2

Jamali, M., Soufizadeh, S., Yeganeh, B., & Emam, Y. (2021). A comparative study of irrigation techniques for energy flow and greenhouse gas (GHG) emissions in wheat agroecosystems under contrasting environments in south of Iran. *Renewable and Sustainable Energy Reviews*, *139*(December 2020), 110704. https://doi.org/10.1016/j.rser.2021.110704

Jha, C. K., & Gupta, V. (2021). Environmental and Sustainability Indicators Farmer ' s perception and factors determining the adaptation decisions to cope with climate change : An evidence from rural India. *Environmental and Sustainability Indicators*, *10*(March), 100112. https://doi.org/10.1016/j.indic.2021.100112

Juhola, S., Glaas, E., Linnér, B.-O., & Neset, T.-S. (2016). Redefining maladaptation. *Environmental Science and Policy*, *55*, 135–140. https://doi.org/10.1016/j.envsci.2015.09.014

Khoshnevisan, B., Rafiee, S., Omid, M., Yousefi, M., & Movahedi, M. (2013). Modeling of energy consumption and GHG (greenhouse gas) emissions in wheat production in Esfahan province of Iran using arti fi cial neural networks. *Energy*, *52*, 333–338. https://doi.org/10.1016/j.energy.2013.01.028

Knoben, W. J. M., Freer, J. E., & Woods, R. A. (2019). Technical note: Inherent benchmark or not? Comparing Nash- Sutcliffe and Kling-Gupta efficiency scores. *Hydrology and Earth System Sciences*, *July*, 1–7.

Li, W., Yuan, K., Yue, M., Zhang, L., & Huang, F. (2021). Climate Risk Management Climate change risk perceptions , facilitating conditions and health risk management intentions : Evidence from farmers in rural China. *Climate Risk Management*, *32*(February), 100283. https://doi.org/10.1016/j.crm.2021.100283

Logan, T., Bourgault, P., Smith, T. J., Huard, D., Biner, S., Labonté, M.-P., Rondeau-Genesse, G., Fyke, J., Aoun, A., Roy, P., Ehbrecht, C., Caron, D., Stephens, A., Whelan, C., Low, J.-F., & Lavoie, J. (2021). Ouranosinc/xclim: v0.31.0 (v0.31.0). *Zenodo*. https://doi.org/10.5281/zenodo.5649661

Lord, R., & Sakrabani, R. (2019). Ten-year legacy of organic carbon in non-agricultural (brownfield) soils restored using green waste compost exceeds 4 per mille per annum: Benefits and trade-offs of a circular economy approach. *Science of the Total Environment*, *686*, 1057–1068. https://doi.org/10.1016/j.scitotenv.2019.05.174

LWK Niedersachsen. (2012). *AQUARIUS – Dem Wasser kluge Wege ebnen! Projektbericht*. https://www.lwk-niedersachsen.de/index.cfm/portal/6/nav/203/article/12396.html

Maltby, K. M., Simpson, S. D., & Turner, R. A. (2021). Climate Risk Management Scepticism and

perceived self-efficacy influence fishers ' low risk perceptions of climate change. *Climate Risk Management*, *31*(January), 100267. https://doi.org/10.1016/j.crm.2020.100267
Máñez Costa, M., Osorio, J., & Kovalevsky, D. (2017). *IMPREX Deliverable D13.1: Generic Integrative Modeling*.
Maruf, N. I. (2021). Open model-based analysis of a 100 % renewable and sector-coupled energy system – The case of Germany in 2050 Weighted Average Cost of Capital. *Applied Energy*, *288*(September 2020), 116618. https://doi.org/10.1016/j.apenergy.2021.116618
Mendez, M., Maathuis, B., Hein-Griggs, D., & Alvarado-Gamboa, L.-F. (2020). Performance Evaluation of Bias Correction Methods for Climate Change Monthly Precipitation Projections over Costa Rica. *Water*. https://doi.org/10.3390/w12020482
Mitter, H., & Schmid, E. (2021). Informing groundwater policies in semi-arid agricultural production regions under stochastic climate scenario impacts. *Ecological Economics*, *180*(November 2020), 106908. https://doi.org/10.1016/j.ecolecon.2020.106908
Mohammadi, A., Ra, S., Jafari, A., Keyhani, A., Mousavi-avval, S. H., & Nonhebel, S. (2014). Energy use efficiency and greenhouse gas emissions of farming systems in north Iran. *Renewable and Sustainable Energy Reviews*, *30*, 724–733. https://doi.org/10.1016/j.rser.2013.11.012
Monteith, J. L. (1965). Evaporation and environment. *Symposia of the Society for Experimental Biology*, *19*, 205–234.
Moriasi, D. N., Arnold, J. G., Liew, M. W. Van, Bingner, R. L., Harmel, R. D., & Veith, T. L. (2007). Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE*, *50*(3), 885–900.
Moriasi, D. N., Gitau, M. W., Pai, N., & Daggupati, P. (2015). Hydrological and water quality models: Performance measures and evaluation criteria. *Transactions of the ASABE*, *58*(6), 1763–1785. https://doi.org/10.13031/trans.58.10715
Nash, E., & Sutcliffe, V. (1970). River flow forecasting through conceptual models. Part I - A discussion of principles. *Journal of Hydrology*, *10*, 282–290.
Nyang'au, J. O., Mohamed, J. H., Mango, N., Makate, C., & Wangeci, A. N. (2021). Heliyon Smallholder farmers ' perception of climate change and adoption of climate smart agriculture practices in Masaba South Sub-county , Kisii , Kenya. *Heliyon*, *7*(March 2020), e06789. https://doi.org/10.1016/j.heliyon.2021.e06789
Okiria, E., Okazawa, H., Noda, K., Kobayashi, Y., Suzuki, S., & Yamazaki, Y. (2022). *A Comparative Evaluation of Lumped and Semi-Distributed Conceptual Hydrological Models : Does Model Complexity Enhance Hydrograph Prediction ?*
Onyutha, C. (2022). *A hydrological model skill score and revised R-squared*. *53*(1), 51–64. https://doi.org/10.2166/nh.2021.071
ORF. (2021). *Land will Donau-Wasser für Seewinkel*. https://burgenland.orf.at/stories/3095447/
Page, D., Dillon, P., Toze, S., Bixio, D., Genthe, B., & Jime, B. E. (2010). Valuing the subsurface pathogen treatment barrier in water recycling via aquifers for drinking supplies. *Water Research*, *44*(6), 1841–1852. https://doi.org/10.1016/j.watres.2009.12.008
Pastén-Zapata, E., Jones, J. M., Moggridge, H., & Widmann, M. (2020). Evaluation of the performance of Euro-CORDEX Regional Climate Models for assessing hydrological climate change impacts in Great Britain : A comparison of different spatial resolutions and quantile mapping bias correction methods. *Journal of Hydrology*, *584*(July 2019), 124653. https://doi.org/10.1016/j.jhydrol.2020.124653
Piccolo, A. (1996). Humus and Soil Conservation. In *Humic Substances in Terrestrial Ecosystems*.
Pilarova, T., Kandakov, A., & Bavorova, M. (2022). Adaptation of smallholder farmers to climate risks: Remittances and irrigation investment in the Republic of Moldova. *Water Resources and Economics*, *38*. https://doi.org/doi.org/10.1016/j.wre.2022.100200
Rathore, V. S., Nathawat, N. S., Bhardwaj, S., Yadav, B. M., Santra, P., Kumar, M., Shekhawat, R. S., Reager, M. L., Yadav, S. R., Lal, B., Yadava, N. D., Singh, J. P., Kumar, P., Bhaskar, S., & Yadav, O. P. (2022). Alternative cropping systems and optimized management practices for saving groundwater and enhancing economic and environmental sustainability. *Agricultural Water*

Management, *272*.
Rechid, D., Petersen, J., Schoetter, R., & Jacob, D. (2014). Klimaprojektionen für das Modellgebiet Lüneburger Heide. In *Klimawandel in der LÜNEBURGER HEIDE – Kulturlandschaften zukunftsfähig gestalten* (pp. 11–19).
Rossi, R. (2019). *Irrigation in EU agriculture* (Issue December). https://www.europarl.europa.eu/RegData/etudes/BRIE/2019/644216/EPRS_BRI(2019)644216_EN.pdf
Rubio-Martin, A., Pulido-Velazquez, M., Macian-Sorribes, H., & Garcia-Prats, A. (2020). System Dynamics Modeling for Supporting Drought-Oriented Management of the Jucar River. *Water*, *12*. https://doi.org/10.3390/w12051407
Samaniego, L., Thober, S., Kumar, R., Wanders, N., Rakovec, O., Pan, M., Zink, M., Sheffield, J., Wood, E. F., & Marx, A. (2018). Anthropogenic warming exacerbates European soil moisture droughts. *Nature Climate Change*, *8*(5), 421–426. https://doi.org/10.1038/s41558-018-0138-5
Sapino, F., Dionisio, C. P., Guti, C., García-prats, A., & Pulido-velazquez, M. (2022). *Influence of crop-water production functions on the expected performance of water pricing policies in irrigated agriculture*. *259*(September 2021). https://doi.org/10.1016/j.agwat.2021.107248
Scheihing, K. W. (2019). Klimawandel in Niedersachsen und mögliche Folgen für die Grundwasserbewirtschaftung : ein Review. *Hydrologie Und Wasserbewirtschaft*, *April*. https://doi.org/10.5675/HyWa_2019.2_2
Schulz, E., & Wendland, F. (2014). Grundwasserhaushaltssituation und Anpassungsstrategien bei Knappheit. In *Kursbuch: Klimaanpassung* (pp. 62–63). KLIMZUG-NORD Verbund. http://klimzug-nord.de/file.php/2014-03-20-KLIMZUG-NORD-Verbund-Hrsg.-2014-Kursbuch-Klimaanpassu
Senatore, A., Fuoco, D., Maiolo, M., Mendicino, G., Smiatek, G., & Kunstmann, H. (2022). Evaluating the uncertainty of climate model structure and bias correction on the hydrological impact of projected climate change in a Mediterranean catchment. *Journal of Hydrology: Regional Studies*, *42*, 101120. https://doi.org/10.1016/j.ejrh.2022.101120
Shen, Y., Li, S., Chen, Y., Qi, Y., & Zhang, S. (2013). Estimation of regional irrigation water requirement and water supply risk in the arid region of Northwestern China 1989 – 2010. *Agricultural Water Management*, *128*, 55–64. https://doi.org/10.1016/j.agwat.2013.06.014
Solaiman, Z. M., Yang, H., Archdeacon, D., Tippett, O., Tibi, M., & Whiteley, A. S. (2019). Humus-Rich Compost Increases Lettuce Growth, Nutrient Uptake, Mycorrhizal Colonisation, and Soil Fertility. *Pedosphere*, *29*(2), 170–179. https://doi.org/10.1016/S1002-0160(19)60794-0
Soriano, E., Mediero, L., & Garijo, C. (2019). Selection of Bias Correction Methods to Assess the Impact of Climate Change on Flood Frequency Curves. *Water*.
Sterman, J. D. (2000). *Bussiness Dynamics. Systems Thinking and Modeling for a Complex World.* (J. J. Shelstad (ed.)). McGraw-Hill Higher Education.
Teixeira, E. I., Ruiter, J. De, Ausseil, A., Daigneault, A., Johnstone, P., Holmes, A., Tait, A., & Ewert, F. (2017). Adapting crop rotations to climate change in regional impact modelling assessments. *Science of the Total Environment*. https://doi.org/10.1016/j.scitotenv.2017.10.247
Torppa, K. A., & Taylor, A. R. (2022). Alternative combinations of tillage practices and crop rotations can foster earthworm density and bioturbation. *Applied Soil Ecology*, *175*(August 2021), 104460. https://doi.org/10.1016/j.apsoil.2022.104460
Tumsa, B. C. (2022). Performance assessment of six bias correction methods using observed and RCM data at upper Awash basin , Oromia , Ethiopia. *Water and Climate Change*, *13*(2), 664–683. https://doi.org/10.2166/wcc.2021.181
Turral, H., Burke, J., Faures, J. M., & Faures, J. M. (2011). Climate change, water and food security. In *FAO Water Reports*. https://doi.org/ISSN 1020-1203
Umweltbundesamt. (2014). Entwicklung der spezifischen Treibhausgas-Emissionen des deutschen Strommix in den Jahren 1990 bis 2013. In *Umweltbundesamt* (Vol. 23). http://www.umweltbundesamt.de/sites/default/files/medien/376/publikationen/climate_change_23_2014_komplett.pdf
Umweltbundesamt. (2018). *Struktur der Flächennutzung*.

https://www.umweltbundesamt.de/daten/flaeche-boden-land-oekosysteme/flaeche/struktur-der-flaechennutzung#textpart-2

Valencia Cotera, R., Egerer, S., & Máñez Costa, M. (2022). Identifying Strengths and Obstacles to Climate Change Adaptation in the German Agricultural Sector : A Group Model Building Approach. *Sustainability*, *14*(4). https://doi.org/10.3390/su14042370

Valencia Cotera, R., Guillaumot, L., Sahu, R.-K., Nam, C., Lierhammer, L., & Costa, M. M. (2022). An assessment of water management measures for climate change adaptation of agriculture in Seewinkel. *Science of the Total Environment*.

Valhondo, C., Martínez-landa, L., Carrera, J., Díaz-cruz, S. M., Amal, S., & Levantesi, C. (2020). Chemosphere Six artificial recharge pilot replicates to gain insight into water quality enhancement processes. *Chemosphere*, *240*. https://doi.org/10.1016/j.chemosphere.2019.124826

Vennix, J. A. M. (1996). *Group Model Building: Facilitating Team Learning Using System Dynamics*. John Wiley & Sons Ltd.

Wang, X., Zhang, J., & Ali, M. (2016). *Impact of climate change on regional irrigation water demand in Baojixia irrigation district of China*. 233–247. https://doi.org/10.1007/s11027-014-9594-z

Williams, D. S. (2020). Enhancing Autonomy for Climate Change Adaptation Using Participatory Modeling. *Weather, Climate and Society*, *12*, 667–678. https://doi.org/10.1175/WCAS-D-20-0024.1

Wittenberg, H. (2015). *Groundwater Abstraction for Irrigation and Its Impacts on Low Flows in a Watershed in Northwest Germany*. 566–576. https://doi.org/10.3390/resources4030566

Wriedt, G. (2019). *Grundwasserbericht Niedersachsen Sonderausgabe zur Grundwasserstandssituation im Trockenjahr 2018*. https://www.nlwkn.niedersachsen.de/download/140352/Sonderbericht_Grundwasserstaende_im_Trockenjahr_2018.pdf

Yu, M., Mapuskar, S., Lavonen, E., Oskarsson, A., Mccleaf, P., & Lundqvist, J. (2022). Artificial infiltration in drinking water production : Addressing chemical hazards using effect-based methods. *Water Research*, *221*(April), 118776. https://doi.org/10.1016/j.watres.2022.118776

Zhang, K., Maltais-landry, G., & Liao, H. (2021). How soil biota regulate C cycling and soil C pools in diversified crop rotations. *Soil Biology and Biochemistry*, *156*, 108219. https://doi.org/10.1016/j.soilbio.2021.108219

Zhao, R., Liu, Y., Tian, M., Ding, M., Cao, L., Zhang, Z., Chuai, X., Xiao, L., & Yao, L. (2018). Impacts of water and land resources exploitation on agricultural carbon emissions: The water-land-energy-carbon nexus. *Land Use Policy*, *72*, 480–492. https://doi.org/10.1016/j.landusepol.2017.12.029

Zink, M., Samaniego, L., Kumar, R., Thober, S., Mai, J., Schäfer, D., & Marx, A. (2016). The German drought monitor. *Environmental Research Letters*, *11*(7), 1–9. https://doi.org/10.1088/1748-9326/11/7/074002

APPENDIX G: CLIMATE MODELS ENSEMBLES

Table 4.1 Model ensembles used for each RCP

Regional Climate Model	Driver Model	Run type
CLMcom-CCLM4-8-17	CCCma-CanESM2	RCP 8.5
CLMcom-CCLM4-8-17	CNRM-CERFACS-CNRM-CM5	RCP 4.5
CLMcom-CCLM4-8-17	CNRM-CERFACS-CNRM-CM5	RCP 8.5
CLMcom-CCLM4-8-17	ICHEC-EC-EARTH	RCP 2.6
CLMcom-CCLM4-8-17	ICHEC-EC-EARTH	RCP 4.5
CLMcom-CCLM4-8-17	ICHEC-EC-EARTH	RCP 8.5
CLMcom-CCLM4-8-17	MIROC-MIROC5	RCP 8.5
CLMcom-CCLM4-8-17	MOHC-HadGEM2-ES	RCP 4.5
CLMcom-CCLM4-8-17	MOHC-HadGEM2-ES	RCP 8.5
CLMcom-CCLM4-8-17	MPI-M-MPI-ESM-LR	RCP 2.6
CLMcom-CCLM4-8-17	MPI-M-MPI-ESM-LR	RCP 4.5
CLMcom-CCLM4-8-17	MPI-M-MPI-ESM-LR	RCP 8.5
DMI-HIRHAM5	NCC-NorESM1-M	RCP 4.5
DMI-HIRHAM5	NCC-NorESM1-M	RCP 8.5
GERICS-REMO2015	ICHEC-EC-EARTH	RCP 2.6
GERICS-REMO2015	IPSL-IPSL-CM5A-MR	RCP 2.6
GERICS-REMO2015	MIROC-MIROC5	RCP 2.6
GERICS-REMO2015	MOHC-HadGEM2-ES	RCP 2.6
GERICS-REMO2015	MPI-M-MPI-ESM-LR	RCP 8.5
GERICS-REMO2015	NCC-NorESM1-M	RCP 2.6
GERICS-REMO2015	NCC-NorESM1-M	RCP 8.5
GERICS-REMO2015	NOAA-GFDL-ESM2G	RCP 2.6
IPSL-INERIS-WRF331F	IPSL-IPSL-CM5A-MR	RCP 4.5
IPSL-INERIS-WRF331F	IPSL-IPSL-CM5A-MR	RCP 8.5
KNMI-RACMO22E	CNRM-CERFACS-CNRM-CM5	RCP 4.5
KNMI-RACMO22E	CNRM-CERFACS-CNRM-CM5	RCP 8.5
KNMI-RACMO22E	ICHEC-EC-EARTH	RCP 2.6
KNMI-RACMO22E	ICHEC-EC-EARTH	RCP 4.5
KNMI-RACMO22E	ICHEC-EC-EARTH	RCP 8.5
KNMI-RACMO22E	IPSL-IPSL-CM5A-MR	RCP 8.5
KNMI-RACMO22E	MOHC-HadGEM2-ES	RCO 4.5
KNMI-RACMO22E	MOHC-HadGEM2-ES	RCO 8.5
KNMI-RACMO22E	MPI-M-MPI-ESM-LR	RCP 8.5
KNMI-RACMO22E	NCC-NorESM1-M	RCP 8.5
MPI-CSC	MPI-M-MPI-ESM-LR	RCP 2.6
MPI-CSC	MPI-M-MPI-ESM-LR	RCP 4.5
MPI-CSC	MPI-M-MPI-ESM-LR	RCP 8.5
SMHI-RCA4	CNRM-CERFACS-CNRM-CM5	RCP 4.5
SMHI-RCA4	CNRM-CERFACS-CNRM-CM5	RCP 8.5
SMHI-RCA4	ICHEC-EC-EARTH	RCP 2.6
SMHI-RCA4	ICHEC-EC-EARTH	RCP 4.5
SMHI-RCA4	ICHEC-EC-EARTH	RCP 8.5
SMHI-RCA4	IPSL-IPSL-CM5A-MR	RCP 4.5
SMHI-RCA4	IPSL-IPSL-CM5A-MR	RCP 8.5
SMHI-RCA4	MOHC-HadGEM2-ES	RCP 2.6
SMHI-RCA4	MOHC-HadGEM2-ES	RCP 4.5
SMHI-RCA4	MOHC-HadGEM2-ES	RCP 8.5
SMHI-RCA4	MPI-M-MPI-ESM-LR	RCP 2.6
SMHI-RCA4	MPI-M-MPI-ESM-LR	RCP 4.5
SMHI-RCA4	MPI-M-MPI-ESM-LR	RCP 8.5
UHOH-WRF361H	MPI-M-MPI-ESM-LR	RCP 8.5

APPENDIX I: MODEL DOCUMENTATION

Table 4.2 Model documentation

Variable	Units	Description
Soil and aquifer dynamics and irrigation demand		
Curve Number (CN)	Dmnl	*The Curve Number characterizes the runoff response of a drainage basin. The parameter reflects land use cover, land treatment, soil type, hydrological condition and previous soil moisture conditions.* **Value:** From 0 to 100 depending on the previously mentioned parameters. Value used in the model: 85.7 ((after calibration) **References:** (Boonstra, 1994; Bos et al., 2009)
S max retention	mm/month	*Represents infiltration after runoff has started. It is related to the soil properties represented by CN.* **Equation:** S = (25400/CN)-254 **Reference:** (Boonstra, 1994; Bos et al., 2009)
Runoff	mm/month	*It represents the portion of water that does not infiltrate and it superficially drains from an area of land. According to the Curve Number Method, runoff only begins if precipitation is greater than 20% of S max retention.* **Equation:** IF THEN ELSE (Pp>(0.2*S max retention), ((Pp-(0.2*S max retention))^2)/(Pp+(0.8*S max retention)) , 0) **Reference:** (Boonstra, 1994; Bos et al., 2009)
Precipitation (Pp)	mm/month	*Condensation of atmospheric water vapor.* **Value:** ERA5 Data **Reference:** https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5
Effective precipitation (Pe)	mm/month	*The fraction of precipitation useful for meeting the crop's water needs.* **Equation:** Pe = 0.8 P 25 if P > 75 mm/month; Pe = 0.6 P 10 if P < 75 mm/month **Reference:** (Brouwer & Heibloem, 1986)
Evapotranspiration (ETP)	mm/month	*Total water loss of water into the atmosphere from a surface.* **Value:** ERA5 Data **References:** https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5
Infiltration	mm/month	*Portion of water entering the soil. It depends on the soil characteristics, the percentage of humidity in the soil and precipitation. In this case it was calculated as the product of precipitation minus runoff.* **Equation:** IF THEN ELSE(Pp-Runoff>0 , Pp-Runoff , 0)

Soil water	mm	*Fraction of water stored in the soil. Water enters through infiltration and leaves the stock either through recharge (when the S is reached) or through outflow (evapotranspiration).* **Equation:** Infiltration-Outflow-Recharge
Outflow	mm/month	*Fraction of soil humidity lost into the environment through evapotranspiration.* **Equation:** IF THEN ELSE((Soil water/TIME STEP)<=0, 0 ,IF THEN ELSE((Soil water/TIME STEP)<=ETP, (Soil water/TIME STEP)=ETP , ETP))
Recharge	mm/month	*Deep percolation. The fraction of water moving into the aquifer. In the model, deep percolation only happens after the S max retention is reached. In other words, when the soil can no longer store water.* **Equation:** IF THEN ELSE((Soil water/TIME STEP)>=S max retention, (Soil water/TIME STEP)-S max retention, 0)+ArtificialRecharge
Artificial recharge	mm/month	*We simulate a scenario where 50% of the industry and drinking water is treated and returned to the aquifer. This is around 297,799.75 m^3/month (ca. 0.2 mm/month).* **Value:** 0.2 mm/month (297,799.75 m3/month) **References:** (ORF, 2021).
Porosity	Dmnl	*The space between soil particles. The portion of soil volume where water can be stored. Dependent on soil particle size.* **Value:** 0.3% (after calibration)
Groundwater	mm	*The volume of water stored in the underground in water permeable rock, rock fractures, or unconsolidated materials like silt, sand and gravel.* **Equation:** ((Recharge-Extraction-Base flow)/Porosity)
Extraction	mm/month	*Volume of water extracted from the aquifer for human use. For example for irrigation, drinking water and water for the industry.* **Equation:** (Agricultural water/(Irrigated area/Total area))+((Industrial water/Total area)*0.001)+((Drinking water/Total area)*0.001)
Total area	km^2	*The total area of the study region including agricultural area and all other land use fractions.* **Value:** 1,454 km2 (total area of the County of Uelzen)
Irrigated area	km^2	*Fraction of the total area irrigated at least once a year.* **Value:** 600 km2 **Reference:** Data provided by the County of Uelzen
Drinking water	m^3/month	*Water extracted from the aquifer for drinking purposes.*

		Value: 533,638 m^3/month **Reference:** Data provided by the County of Uelzen
Industrial water	m^3/month	*Water extracted from the aquifer for industrial purposes.* **Value:** 61,921.5 m^3/month **Reference:** Data provided by the County of Uelzen
Base flow	mm/month	*The volume of water discharged from the aquifer by horizontal flow.* **Equation:** (Groundwater)*α
Recession time (α)	1/month	*The inverse of the time required for water to leave the aquifer by horizontal flow.* **Value:** 9e-07 (after calibration)
Underground runoff	mm/month	*The volume of water discharged from the aquifer into surface waterbodies or flowing horizontally.* **Equation:** (Groundwater)*β
Runoff coefficient (β)	1/month	*The inverse of the time required for water to leave by underground runoff.* **Value:** 0.0166 (after calibration)
Irrigation demand		
Irrigation efficiency (n)	Dmnl	*Represents the irrigation efficiency of the implemented irrigation method. A higher efficiency means less water lost to evapotranspiration or runoff.* **Value:** Dependent on the irrigation method usually between 40 to 95% **Reference:** (Howell, 2003)
Crop factor (Kc)	Dmnl	*Represents the evapotranspiration of the grown crop compared to the reference crop ETo. It is used to determine the crops water needs. The value changes as the crop matures.* **Value:** Each crop has four crops depending on the growth stage. The values usually lay between 0.3 and 1.15. These values are found in manuals. **Reference:** (Brouwer & Heibloem, 1986)
Correction	Dmnl	*This parameter is included in the irrigation demand equation to give more room for calibration.* **Value:** 5.96 (after calibration)
Agricultural water	mm/month	*This parameter represents the irrigation water demand (IWD). It is calculated using the irrigation equation described in Chapter 3. The IWD is only calculated for the months when crops are irrigated (March until August). In the other months the Kc is set to zero and thus the IWD is also zero.* **Equation:** IF THEN ELSE((((Kc*ETr)-Pe)/(Correction*n))>=0, ((Kc*ETr)-Pe)/(Correction*n) , 0)

		References: (Brouwer & Heibloem, 1986; Shen et al., 2013; Wang et al., 2016)
Monthly irrigation	m^3/month	*Converts the value of agricultural water (IWD) from mm/month to m^3/month.* **Equation:** Agricultural water*10
Energy, costs and emissions		
Energy	kWh	*Total energy consumed during the modeling period.* **Equation:** Consumption (added every month)
Consumption	kWh/month	*Monthly energy consumption due to irrigation.* **Equation:** Monthly irrigation*Energy per m3
Energy per m^3	kWh/m^3	*Average electrical energy required for irrigation per cubic meter of water used.* **Value:** 0.6 kWh/m^3 **References:** Data provided by the LWK Niedersachsen
Costs	€	*Total costs generated during the modeling period.* **Equation:** Generated (added every month)
Generated	€/month	*Monthly costs generated due to irrigation, machinery and work costs.* **Equation:** (Diesel consumption*Diesel price)+(Consumption*kWh price)+(Monthly irrigation*Work cost)+(Monthly irrigation *Repairs cost)
kWh price	€/kWh	*Cost in euros per kWh based on the average historical price.* **Value:** 0.3
Diesel price	€/liter	*Cost in euros per liter of diesel based on the average historical price.* **Value:** 1.25
Work cost	€/m^3	*Average operational costs of irrigation per cubic meter of water used for irrigation.* **Value:** 0.02 **References:** Data provided by the LWK Niedersachsen
Repairs cost	€/m^3	*Average repair costs of irrigation per cubic meter of water used for irrigation.* **Value:** 0.015 **References:** Data provided by the LWK Niedersachsen
Diesel consumption	liter/ha	*Average diesel consumption per hectare.* **Equation:** IF THEN ELSE(Kc = 0, 0 , 9.17) **Reference:** Data provided by the LWK Niedersachsen
CO_2	kg CO_2	*Total emissions generated during the modeling period.*

		Equation: Emissions (added monthly)
Emissions	Kg CO_2/month	*Average monthly emissions generated due to energy and fuel consumption.* **Equation:** (Emissions per kWh*Consumption)+(Diesel consumption*Emissions per liter of fuel)
Emissions per liter of fuel	kg CO_2/liter	*CO2 emissions per liter of diesel burned.* **Value:** 2.67
Emissions per kWh	Kg CO_2/kWh	*CO2 emitted for by the generation of electricity. The value is an average of the electricity mix in Germany including all generation methods.* **Equation:** IF THEN ELSE(Condition=0, BAU , NetoNull)
Condition	Dmnl	*Used to activate one of the two possible emissions scenarios.* Value: 0 or 1
BAU	Kg/kWh	*The BAU scenario follows the current emissions trend in the energy sector in Germany.* **Value:** Decreasing every year
NetoNull	Kg/kwh	*The NetoNull or Net-Zero scenario follows a trend in which the energy sector becomes carbon neutral in 2050.* **Value:** Decreasing every year

APPENDIX J: CROP FACTORS OF CURRENT CROP ROTATION AND NEW CROP ROTATION

As seen in Table 4.3 and 4.4 all three crops have similar crop factors and growing stages. By averaging these values we conclude with a fictitious, but representative, crop with the following *Kc* and days per grow stage (Table 4.5). This also leave us with a growing season of 171 days, which matches with the growing season in NELS, as it extends from March until the middle of August.

Table 4.3. Crop factor (Kc) for the three crops (Brouwer & Heibloem, 1986). The factor changes with the plant growing stage but they are very similar across the three crops.

	Initial	**Crop development**	**Mid-season**	**Late**
Corn	0,40	0,80	1,15	1,00
Sugar beet	0,40	0,80	1,15	0,80
Potato	0,40	0,75	1,15	0,85
Average	0,40	0,78	1,15	0,88

Table 4.4. Days per growing stage for each crop (Brouwer & Heibloem, 1986). The values are also similar for the three crops.

	Initial	**Crop development**	**Mid-season**	**Late**
Corn	30	50	60	40
Sugar beet	25 - 45	35 - 65	60 - 80	40
Potato	25 - 30	30 - 35	30 - 50	20 - 30
Average	35	44	57	35

Table 4.5. Kc and days per growing stage for a fictitious crop representing the average of the three crops.

	Initial	**Crop development**	**Mid-season**	**Late**
Kc	0,40	0,78	1,15	0,88
Days	35	44	57	35

To simulate the CRP scenario we propose a new crop rotation based on less water-demanding crops with a shorter vegetation period (Table 4.6). These crops have similar Kcs. The Kc of the suggested new crop rotation are not drastically lower than the real crop rotation (Table 4.5). However, the vegetation period is shortened from 171 days to 132 days.

Table 4.6. A hypothetical new rotation with less water demanding crops such as sorghum, barley, millet, soy or lentils. These crops have also shorter growing periods. Crop factors and days per growing stage according to Brouwer & Heibloem, (1986).

Crop Factor (Kc)				
Crop	**Initial stage**	**Crop development**	**Mid-season**	**Late season**
Averaged	0.35	0.73	1.12	0.65
Vegetation Period				
Crop	**Initial stage**	**Crop development**	**Mid-season**	**Late season**
Averaged	17 days	28 days	56 days	31 days

APPENDIX K. REAL IRRIGATION TREND COMPARED TO THE IRRIGATION DEMAND EQUATION

The irrigation data for the county of Uelzen for the period 2002 to 2018 was the only observation data available. This is however annual data and the model and the irrigation equation function at a monthly resolution. To calculate the annual IWR and compare it to the only observation available, the values of the growing season (March to August) were added.

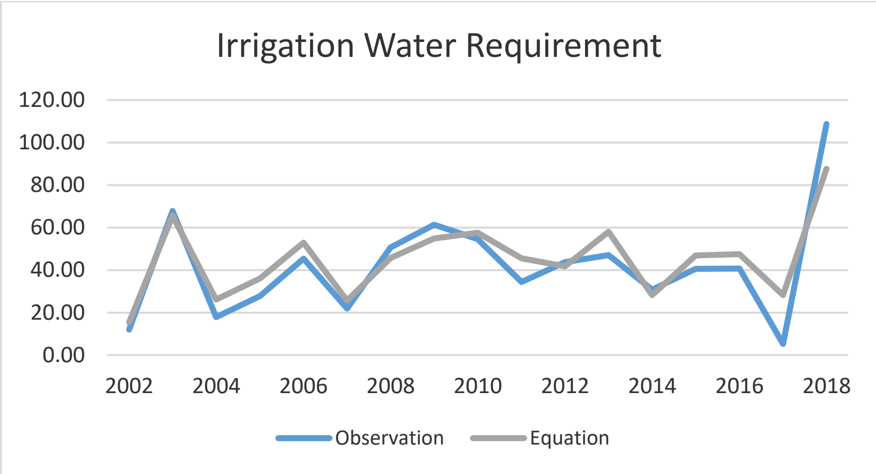

Figure 4.8. Comparison between observed irrigation water use and the irrigation equation.

With an irrigation efficiency of 53%, which is in the range of big gun sprinkler irrigation (Bos et al., 2009b; Howell, 2003), the irrigation equation predicted the observed IWR with a high degree of accuracy (R = 0.95 and R2 = 0.89) as seen in Figure 4.8 and Table 4.7.

Table 4.7. Observed irrigation water use in Uelzen and the results of the irrigation equation

Uelzen	Data	Equation
Year	mm/a	mm/a
2002	11,97	15,44
2003	67,88	65,55
2004	17,81	26,15
2005	27,77	36,07
2006	45,44	52,87
2007	21,84	25,62
2008	50,65	45,75
2009	61,30	54,91
2010	54,54	57,50
2011	34,39	45,56
2012	43,67	41,81
2013	47,03	58,00
2014	30,84	28,24
2015	40,57	46,85
2016	40,71	47,44
2017	5,23	28,22
2018	108,74	87,71

APPENDIX L: MODEL EQUATIONS

These equations compose the SD model used in in Chapter 4. To reproduce the hydrological model of Uelzen, the equations can be directly copied and pasted into Vensim. To do this, open Vensim and click View>As Text. Once the visualization has changed, paste the equations. To view the model as stocks and flows, click View>As Sketch.

To run simulations, the model has to be fed with precipitation (Pp), evapotranspiration (ETP) and the crop factors (Kc) data. This data is stored in external files and fed to the model through either the "GET XLS DATA" function in Vensim or using the Python package "PySD". Because of this, in the equations, the values of Pp, ETr and Kc are given as 1.

However, the model should not be directly applied to a different region. The values of the constants shown in these equations, for example CN or porosity, were calibrated for Uelzen. These values evidently will not apply in other regions. Because of this, before running any type of simulations for other regions, the model has to be calibrated.

```
Monthly irrigation=
	Agricultural water*10
	~	m3/Month
	~		|

Agricultural water=
	IF THEN ELSE((((Kc*ETP)-Pe)/(Correction*n))>=0, ((Kc*ETP)-Pe)/(Correction*n), 0)
	~	mm/Month
	~	The formula is calculating the water withdrawn based on the area of 600 \
		km2 but it has to be transformed to 1454 to count the total area and how \
		many mm it subtracts from the groundwater.
	|

River Inflow=
	0.0166
	~	
	~		|

return flow=
	0.0108
	~	 [0.15,0.37]
	~		|

River flow=
	Groundwater*River Inflow
	~	
	~		|

Recharge=
	IF THEN ELSE((Soil water/TIME STEP)>=S max retention, (Soil water/TIME STEP)-S max
retention\
		, 0 )+Artificial Recharge
```

```
	~	mm/Month
	~	IF THEN ELSE((Soil water/TIME STEP)>=S max retention, (Soil water/TIME STEP)-S max \
		retention, 0 )+ArtificialRecharge+DELAY1
		(((Agricultural water/(Irrigated area/Total area))*return flow) , months )
	|

months=
	2.12
	~
	~		|

Groundwater= INTEG (
	((Recharge-Extraction-Base flow-River flow)/Porosity),
		0)
	~	mm
	~		|

Extraction=
	(Agricultural water/(Irrigated area/Total area))+((Industrial water/Total area)*0.001\
		)+((Drinking water/Total area)*0.001)
	~	mm/Month
	~		|

Infiltration=
	IF THEN ELSE( Pp-Runoff>0 , Pp-Runoff , 0 )
	~	mm/Month
	~		|

Generated=
	(Diesel consumption*Diesel price)+(Consumption*kWh price)+(Monthly irrigation*Work cost\
		)+(Monthly irrigation
	*Repairs cost)
	~	euro/Month
	~		|

Allowed amount=
	70.34
	~	mm/year
	~	With the data of Uelzen, on average between 2002 and 2008, 51,458,693.71 \
		m3/year were allowed to be extracted. With an area of 60,000 ha = 85.76 \
		mm/year and with an area of 73,156 ha = 70.34 mm/year. Maximum allowed \
		including industrial water and drinking water.
	|

Aquifer yield=
	91.95
	~	mm/year
	~	The data of Uelzen says 67,270,000 m3/yr. If we use the area of 60,000 ha \
		then = 112.12 mm/year if we use 73,156 ha then = 91.95 mm/year.
	|
```

```
Irrigated area=
	600
	~	km2
	~		|

Emissions=
	(Emissions per kWh*Consumption)+(Diesel consumption*Emissions per liter of fuel)
	~	kg/Month
	~		|

BAU:INTERPOLATE::=
	1
	~
	~		|

CO2= INTEG (
	Emissions,
		0)
	~
	~		|

Condition=
	0
	~	 [0,1,1]
	~		|

Consumption=
	Monthly irrigation*Energy per m3
	~	kWh/Month
	~		|

Past=
	Energy
	~
	~		|

Costs= INTEG (
	Generated,
		0)
	~
	~		|

Covered=
	Costs
	~
	~		|

Diesel consumption=
	IF THEN ELSE(Kc = 0, 0 , 9.17 )
	~	liter/hectare
	~	Average tracktor diesel consumption per hectare (Fricke)
```

|

Diesel price=
1.25
~ euro/liter
~ |

Drinking water=
533638
~ m3/Month
~ |

Emissions per kWh=
IF THEN ELSE(Condition=0, BAU , NetoNull)
~ kg/kWh
~ |

Emissions per liter of fuel=
2.67
~ kg/liter
~ 2.76 kg of CO2 per Liter of diesel
|

Emitted=
CO2
~
~ |

Energy= INTEG (
Consumption,
0)
~
~ |

Total area=
1454
~ km2
~ |

ETP:INTERPOLATE::=
1
~
~ |

Work cost=
0.02
~ euro/m3
~ |

Industrial water=
61921.5
~ m3/Month

```
	~		|

NetoNull:INTERPOLATE::=
	1
	~	
	~		|

Outflow=
	IF THEN ELSE((Soil water/TIME STEP)<=0, 0 ,IF THEN ELSE((Soil water/TIME STEP)<=ETP,\
		(Soil water/TIME STEP)=ETP , ETP ))
	~	mm/Month
	~		|

Repairs cost=
	0.015
	~	euro/m3
	~		|

kWh price=
	0.3
	~	euro/kWh
	~	€/kWh
		https://bit.ly/2UU2VwR
	|

Energy per m3=
	0.6
	~	kWh/m3
	~	Electricity = 0,6 kWh/m3
		Diesel = 0,14 l/m3
	|

Water Balance=
	Pp-Runoff-Infiltration
	~	mm/Month
	~		|

Pe=
	IF THEN ELSE(Pp>75, (0.8*Pp)-25 , (0.6*Pp)-10 )
	~	
	~		|

Volume=
	Thickness+Groundwater
	~	
	~		|

Artificial Recharge=
	0
	~	 [0,6.54,0.02]
	~		|
```

Kc:INTERPOLATE::=
1
~ Dmnl
~ |

Correction=
5.96
~
~ |

Base flow=
(Groundwater)*Recesion time
~ mm/Month
~ |

Thickness=
10128
~ m [0,150,1]
~ |

ActualET=
Outflow+(Agricultural water*0.35)
~ mm/Month
~ |

n=
0.716
~ Dmnl [0,1,0.01]
~ Irrigation Efficiency Howell Table 1 - Moving big gun n = 65
|

Runoff=
IF THEN ELSE (Pp>(0.2*S max retention), ((Pp-(0.2*S max retention))^2)/(Pp+(0.8*S max
retention
)) , 0)
~ mm/Month
~ |

CN=
85.7
~ Dmnl [0,100,1]
~ Curve Number Table 4.2 Row Crops Soil A or B
|

Recesion time=
9e-07
~ 1/Month [1e-06,0.5,0.0001]
~ 1/recession time
|

Porosity=
0.3

```
	~	Dmnl [0,1,0.01]
	~		|

Pp:INTERPOLATE::=
	1
	~	mm/Month
	~		|

S max retention=
	(25400/CN)-254
	~	mm/Month
	~		|

Soil water= INTEG (
	Infiltration-Outflow-Recharge,
		160)
	~	mm
	~		|

********************************************************
	.Control
********************************************************~
		Simulation Control Parameters
	|

FINAL TIME  = 1140
	~	Month
	~	The final time for the simulation.
	|

INITIAL TIME  = 1
	~	Month
	~	The initial time for the simulation.
	|

SAVEPER  =
        TIME STEP
	~	Month [0,?]
	~	The frequency with which output is stored.
	|

TIME STEP  = 1
	~	Month [0,?]
	~	The time step for the simulation.
	|
```

CHAPTER 5: *Summary, Conclusions, Limitations and Further Research*

5.1 SUMMARY

This study included a qualitative (Chapter 2) and quantitative analysis (Chapter 3 and Chapter 4) of climate change adaptation for agriculture. The quantitative analysis was performed in two research areas: Seewinkel in Austria and Lower Saxony in Germany. The qualitative analysis of the study showed that there is a common knowledge gap in local climate change adaptation as evidence of the effectiveness of adaptation measures was lacking in both regions. Through the implementation of GMB, the study has shown that understanding the stakeholders' perspectives is beneficial to identify the structure of the system, explore adaptation plans and to understand the stakeholders' climate risk perceptions.

Through the implementation of a quantitative analysis the study has shown that understanding the effect of climate change adaptation measures can help adaptation planning by promoting the selection of the most efficient measures to adapt to climate change. At the same time, measures with low impact can be avoided or reserved as the last step in adaptation. Finally, the study also showed that adapting to climate change has additional benefits such as: preserving local natural resources, reducing energy and costs and have a mitigating effect by lowering indirect emissions.

The study started in Chapter 2 with the implementation of a participatory approach in NELS; namely GMB. During the GMB process twenty local stakeholder were engaged and included in the development of a qualitative model. The qualitative model depicts the structure of the system according to the stakeholders' perceptions. The model describes the interactions between agriculture, local water resources, socioeconomics and the climate. In addition to understanding the structure of the system, the GMB process also helped to understand the stakeholders' climate risk perceptions, adaptation intentions and determine if adaptation measures are being planned or have already been implemented.

The study continued in Chapter 3 with the development of a quantitative SD model. The model is based on the system description provided by the stakeholders in Chapter 2. The SD model was then calibrated and tested in Seewinkel; an important agricultural area in Austria with remarkably similar characteristics to NELS. Like NELS, Seewinkel also lacks studies researching the effectiveness of the adaptation measures suggested by stakeholders. Therefore, the SD model was used to help close this gap by testing the effectiveness of the adaptation measures to reduce IWD and preserve the local water resources. The model was successfully implemented and yielded the first study in Seewinkel to make a ranking of agricultural adaptation measures.

In Chapter 4 of this study, the SD model was recalibrated and adapted to the county of Uelzen. Uelzen is the district in NELS with the highest IWD. In Chapter 4, the adaptation measures that were suggested by local stakeholders and recorded in Chapter 2 were tested. While other studies have already focused on the county of Uelzen and the possible adaptation measures that can be implemented, no previous study was found, in which adaption measures were analyzed and ranked by effectiveness. The analysis of Chapter 4 yielded similar results to Chapter 3.

5.2 CONCLUSIONS

This work was performed with the intention of supporting climate change adaptation for agriculture, particularly in the light of projected increases in the severity of droughts. Adapting agriculture to climate change is a crucial step of the climate change adaptation process, as it will help to ensure food security for the future and strengthen the preservation of water resources. However, evidence of the effectiveness and systemic effect of adaptation measures is usually lacking at a regional to local scale. This makes the planning and implementation of adaptation measures challenging and it could lead to poor results. The lack of information might cause stakeholders to implement measures, which are highly costly but have a low or no valuable impact or could lead to maladaptation. By analyzing the effect of implementing adaptation measures, it is possible to (I) Evaluate the potential trade-offs of adaptation; (II) Focus on the implementation of measures with high impact; (III) Avoid the implementation of costly measures with low impact; and (IV) Consider the effect that adaptation measures could have on other spheres such as water resources.

However, before implementing any actions, and in order to avoid maladaptation, it is paramount to understand three key points. First, the structure of the system. Without a deep understanding of the system, it is not possible to determine the full effect that adaptation measures would have and pinpoint unsought outcomes. Second, if adaptation measures have already been planned or implemented. This knowledge can avoid repeating past errors but it is also the base to comprehend, which problems stakeholders are attempting to solve. Third, stakeholders' climate perceptions. Stakeholders with low climate risk perceptions will normally discard adaptation as their incorrect perceptions lead them to believe that climate change adaptation is not needed.

Chapter 2 of this study showed that NELS was unprepared to deal with climate change at the time the study took place. Stakeholder were aware of climate change but their climate risk perception was low. This means that they lacked a deep understanding of the effect that climate change could have on the local water resources and on the local agricultural systems. At the same time, most of the stakeholders were aware of measures that could be implemented to adapt to climate change, however, no measures were being implemented due to the high initial investments and the low climate risk perceptions. To increase the resilience of the region, this study has proposed three solutions. First, climate change communication as a method to improve the stakeholders' climate risk perceptions. Second, large economic incentives as a method to kick start the adaptation process and finance its implementation. Third, updating the water management regulation to include and consider the effects that climate change will have on the local water resources. **The innovative aspect of this study is that, at the point the study took place, no other GMB process had been implemented in NELS. This makes**

it the first participatory modeling approach to (I) give a qualitative insight into the structure of the agricultural and hydrological systems in NELS; (II) reflect the stakeholders' climate risk perceptions; and (III) compile a record of adaptation measures suggested and considered by local stakeholders.

Chapter 3 of this study presented the development of an original hydrological model in SD. The results of the calibration showed that, if hydrological and climate observational data are available, the developed SD model can be calibrated to have a high correlation ($R^2 = 0.85$) with unconfined aquifers; at least in regions of up to 450 km^2. The study showed that adapting agriculture in Seewinkel to climate change has additional benefits besides reducing the IWD. The main additional benefit is that adaptation can help preserve the saline lakes habitat. The study confirmed that shifting to less water demanding crops and increasing the irrigation efficiency are viable adaptation strategies for Seewinkel. The artificial recharge of the aquifer, while still beneficial, does not reduce extractions, has less noticeable effects and it depends on external water. Because of this, farmers are the most influential actor. This group should however, not be seen as the only accountable to implement adaptation as usually, implementing adaptation measures requires high initial investments and systemic shifts that could negatively affect farms and the local economy. Farmers therefore require support from decision makers to reach national and regional adaptation goals. Finally, the project suggested by the local authorities to artificially recharge the aquifer has proved, under this analysis, to be the less beneficial measure for the aquifer and it does not help farmers adapt to climate change. **This study has two innovative aspects. First, it presents an original hydrological model, which can be used to perform similar analyses in other regions**. This original model could be coupled to other SD models to perform more complex socio-economic analyses with a hydrological component**. Second, this is the first study in Seewinkel to perform a systemic analysis of the effectiveness of climate change adaptation measures.** Previous studies have focused on the aquifer, the state of the saline lakes, and on the farmers perceptions. However, no previous study has brought the three aspects together to perform a systemic analysis.

Chapter 4 of this study presented the implementation of the hydrological SD model in Uelzen. The results of this study showed that changing crops and increasing irrigation efficiency is also strongly beneficial for Uelzen to reduce IWD. Humification, although it is a slow process, can have strong benefits by the end of the century. The results also confirmed that reusing water by storing it in the aquifer has an almost negligible effect. Therefore, in this region farms are also the most influential actor. The results also showed the importance of reaching Net-Zero by 2050. Finally, the study showed that adapting to climate change could have additional benefits for farmers as it can reduce their energy use and costs. Adapting farms to climate change has, therefore, a mitigating effect as it reduces the indirect emissions caused by energy use. As mentioned earlier, farmers should not be held as the only responsible to implement adaptation, as this process is highly costly and it requires planning at a systemic level. **The innovative aspect of this study is that it presents the first study in Uelzen to analyze the systemic effect that climate change adaptation measures could have on both, agriculture and the aquifer.** While previous projects have focused on agriculture, hydrology and climate change modelling in NELS, no previous study had made an analysis of the long-term effectiveness of adaptation measures including these three aspects.

The results of this study are now available to be shared with local stakeholders in Uelzen and Seewinkel. By sharing results with the local stakeholders, this study would be supporting science-based decision making. This study was initiated with stakeholder knowledge and it concludes by making knowledge available to stakeholders in the form of scientific analyses. Because of this, the whole process performed in this study can be described as "closed-loop science" where the knowledge moves from society to science and back to society.

Research Question	Results
RQ1. What is the current state of climate change adaptation in NELS?	The results of Chapter 2 indicate that, NELS is currently unprepared to cope with the effects of climate change. The unpreparedness of NELS mainly lies in the fact that the majority of the adaptation measures suggested by the stakeholders imply large-scale system changes, require high initial investments or imply an economic trade-off. Additionally, not all stakeholders hold correct climate risk perceptions.
RQ1.1 How do stakeholders perceive climate change and drought?	The results of Chapter 2 suggest that stakeholders in NELS are aware of climate change. Many farmers mentioned that the summers are longer and the winters are milder. However, many stakeholders do not have a deep understanding of how climate change could affect the region. This means that their climate risk perception, especially of farmers, is very low. Many farmers also do not seem to relate the increase in drought intensity and frequency to climate change.
RQ1.2 Are systemic adaptation measures being developed and implemented?	The results of Chapter 2 indicate that while many stakeholders in NELS are aware of the steps they should implement to adapt, however, at the time the study took place, no major adaptation efforts were being made at either a farm level or regional level. The resistance to adapt is mainly caused by the high initial investments, the socioeconomic structure of the system and the low climate change risk perception. For example, while many stakeholders are aware that a new crop rotation could be beneficial, almost none are willing to change it. This is because the crop rotation consist of cash crops with a high demand, which makes them easy to sell after the harvest.

RQ1.3 What are the NELS vulnerabilities and possible challenges for adaptation?	The results of Chapter 2 show that NELS has four vulnerabilities that challenge its climate change adaptation process. First, the region's high dependence on irrigation. While irrigation systems can help cope with drought events, they can also give a false sense of security. However, according to the results of Chapter 4, implementing more efficient irrigation methods as an adaptation strategy could be highly beneficial, as it could reduce IWD by 15.5%, increase the aquifer level by 177.05 mm and reduce the costs by 11.4%. Second, the water management regulation. According to Chapter 2, the region has strong water management bodies and a functional water management regulation. However, it does not consider the effects of climate change. Not updating the water management law to consider climate change could cause an inability to cope with drought events, increment water extractions as temperatures rise, and cause high extractions during drought events. These reactions could increase the pressure on the aquifer. However, according to the results of Chapter 4, no long-term negative trends in the aquifer were observed. Third, the crop rotation. The system in NELS is entirely based on three water-demanding cash crops. They have a high IWD and are not ideal for humification. This could lead to an ever-increasing water demand under climate change. The results of Chapter 4 have highlighted the substantial effect that changing the crop rotation could have on the region, as changing crops was the most efficient measure to reduce IWD, promote an increase in the aquifer level and reduce costs. However, achieving this without considerable economic loss, is a major challenge. Lastly, NELS has multiple water users. Irrigation is the main user, extracting a significant amount of water, when compared to the industry and drinking water. Allocating water for all users in the future, especially during drought events, could be one of the main challenges in NELS.
	In regards to the IWD, the results of Chapter 3 and 4 show that, when compared to BAU, changing crops can reduce it by 23.0% in Seewinkel and by 20.7% in Uelzen. Increasing irrigation efficiency could reduce IWD by 23.0% in Seewinkel and by 15.2% in Uelzen. In Uelzen humification could reduce IWD by 7.5%. This means that implementing even a single measure could have significant reductions. This effect could be drastically increased if a combination of measures would be implemented. For example, in Seewinkel a combination of changing crops and increasing irrigation efficiency could

RQ2. How effective are adaptation measures to ensure the viability of agriculture under climate change in NELS and Seewinkel?	reduce IWD by up to 40%. Artificial recharge did not have any effect on the IWD of both regions, as it only increases water availability but it does not influence any agricultural processes. As to the aquifers, the results of Chapter 3 and 4 show that, when compared to BAU, changing crops can increase the aquifer level by an average of 1.1 m in Seewinkel and 0.241 m in Uelzen. Increasing irrigation efficiency could increase the aquifer level by 1.1 m in Seewinkel and 0.177 m in Uelzen. In Uelzen, humification could also benefit the aquifer by increasing its level by 0.118 m. Artificial recharge could have an almost negligible effect in Uelzen by increasing the aquifer level by only 0.003 m and by 0.96 m in Seewinkel. The more pronounced effects in Seewinkel could be explained by several factors. First, the difference in the volume of water extracted in each region. Second, the area of the aquifers as Seewinkel is just 450 km^2 while in Uelzen it is 1,454 km^2. Nevertheless, the results have shown that any adaptation measure that implements changes to the demand side are beneficial for the aquifers of both regions and can prevent overdrafting. In summary, changing crops and increasing irrigation efficiency can be classified as highly effective measures to reduce water demand and avoid overdraft thus ensuring the preservation of the local water resources. Humification is also a highly effective measure to reduce IWD and preserve the aquifer. However, humification is a process that takes decades to complete and it might imply that the crop rotation would have to be changed. Lastly, artificially recharging the aquifer has a low to medium effect on aquifers, when compared to other measures. However, this measure is not recommended, as it does not help farms, and therefore the region, to become more resilient to climate change.
RQ2.1 Which adaptation measures can better adapt agriculture to climate change	The results of Chapter 3 and Chapter 4 show that the most effective adaptation measure for both, Uelzen and Seewinkel, is to change the crop rotation followed by an increase in irrigation efficiency. Both regions rely on the same high water-demanding crops and use the same irrigation method. Because of this, moving into a new crop rotation and investing in new irrigation equipment would highly reduce the IWD. According to Chapter 3, a combination of these two measures would greatly reduce the IWD. Chapter 4 show that, because of its poor soil, Uelzen would also benefit from humification, as it increases the soil water retention and reduces the

without increasing its water demand?	irrigation water demand. Artificial recharge does not reduce IWD in neither region, as it only increases the available water volume. Additionally, artificial recharge has a very small effect on the aquifers, when compared to the other adaptation measures.
RQ2.2 What are the additional benefits of implementing climate change adaptation measures?	The results of this study have shown that implementing climate change adaptation measures is not only beneficial to reduce IWD but they also have additional benefits on the system. First, changing the crop rotation might promote humification (Chapter 2), has a direct effect in reducing the IWD therefore it also reduces pressure on aquifer (Chapter 3 and 4), helps preserve the salt lakes in Seewinkel (Chapter 3), drastically reduces energy use, costs (Chapter 4) and has a mitigating effect by reducing indirect emissions (Chapter 4). Increasing the irrigation efficiency will directly reduce the pressure on the aquifers (Chapter 3 and 4), help preserve the salt lakes in Seewinkel (Chapter 3), benefits farmers by reducing energy consumption and costs (Chapter 4) and help mitigation by reducing indirect emissions (Chapter 4) Promoting humification has many benefits. It promotes aquifer recharge, increases soil water holding capacity and therefore it reduces IWD and reduces pressure on the aquifer, reduces energy use and costs and therefore it can help reduce indirect emissions (Chapter 4). Lastly, artificial recharge increases the aquifer level in Seewinkel (Chapter 3) and only slightly increases it in Uelzen (Chapter 4). Its indirect benefits are mild or none when compared to the other measures.

5.3 LIMITATIONS

While the model developed during this study was sufficient to provide an insight into the effectiveness that adaptation measures could have on agriculture and on the local water resources of irrigation-dependent agricultural areas, the study clearly has limitations that could be bridged with further research. In this section this limitations are discussed and further amendments to this study are suggested.

The fist limitation is that the first part of the study is based on the perceptions of twenty stakeholders. While all of these stakeholders play a strong role in the agriculture and water resources dynamics, the perceptions of twenty persons might not provide the full picture. However, due to time limitations and the high volume of work required to carry on interviews, this study had to set a limit of twenty stakeholders. Additionally, the interviews where done during a specific time period. The stakeholders shared their perceptions of the system during that particular time thus creating a snapshot of the system. However, human perceptions and systems are constantly evolving. Therefore their perceptions and the system itself might have evolved since the time of the interviews. To confirm the results presented in Chapter 2, a second analysis could be performed by interviewing the same stakeholders and then compare the results to the first exercise.

The second limitation is that the SD model developed and implemented in this study is a lumped hydrological model. This has several advantages such as a simpler calibration process and faster results computation. Lumped models are usually sufficient when the goal of the research is to understand general long-term trends and behaviors, however, if the objective of the study requires a higher degree of accuracy, a lumped model may be insufficient. To tackle this first limitation, the model presented in this study can be given spatial distribution by dividing the aquifer in sub-regions and recalibrating the model for each sub-region. This would create a network of lumped models, which could give results with a higher resolution. This implies however, that the information needed to calibrate the model is also available in each sub-region. This means that every sub-region would have to have at least one weather station, a groundwater measuring station, information on land use and historical IWD and so forth. While spatial distribution could offer better results, the higher data requirement could over complicate the process.

The third limitation is that this study looks at the long-term effect that adaptation measures could have and it does not focus on the yearly effect that drought events could have. This means that, while some measures are effective on the long run, they might not be sufficient to cope with extreme drought years. Seasonal droughts could still cause a substantial increase in IWD and thus yearly spikes in energy and water use. These spikes in IWD during drought periods could cause farms to become insolvent during those years. This limitation could be compensated by performing an additional analysis. This new analysis should specifically focus on the effect that climate extremes would have on IWD and local water resources during the next eighty years. By including climate extremes in the analysis it would be possible to determine if adaptation measures are also efficient to buffer seasonal variations.

The fourth limitation is that the economic section of the model is highly restricted. The model only calculates costs but it does not calculate economic profits. Therefore, it is not possible to know if farms will become unprofitable; even after implementing adaptation. Additionally, the economic costs of implementing adaptation measures is not considered. These limitations are present because the goal of this research was not to examine the economic advantages of implementing adaptation measures, but to understand how efficient they are to reduce IWD and preserve local water resources during the rest of the 21st century. However, to mend this limitation, the model could include a yield equation to calculate the harvest and a socio-economic sub-model to calculate the profits after selling the yield. By doing this, it would be possible to use the harvest as a reference factor to determine if adaptation measures are also useful to keep yields stable; even under climate change conditions. In the same sub-model, the costs of implementing adaptation could also be included as an annual fix cost or one-time investments.

The fifth limitation is that the model only considers indirect emissions caused by electricity use and it does not include the emissions caused directly by agricultural activities such as fertilizer application. There is a close relationship between humidity in the soil and efficient fertilizer application. To close this gap the model would also have to include equations to calculate the emissions per hectare. Bringing the third and fourth limitation together, the model could benefit from an agricultural sub-model. With this additional sub-model, it would be possible to relate the crops' requirements to IWD, the climate and fertilizer use. By doing this, the agricultural sub-model would close the loop and thus give a more complete view of the system. Therefore, by including an agricultural sub-model the analysis of the effectiveness of adaptation measures would offer a more complete glimpse.

5.4 FURTHER RESEARCH

In addition to the suggested analysis described in the Limitations section, several additional research opportunities not related to the limitations of this study were also identified. The first research opportunity is to implement a study to review and suggest economic methods to promote climate change adaptation in the studied regions. This could be done, for example, through grants, initiatives or similar economic incentives. A common denominator observed during the analysis presented in Chapter 2 is that stakeholders do not implement adaptation measures because of the high initial investments required. At the same time, agricultural systems are still economically viable. This discourages adaption as long as the current practices are still profitable. Therefore, further research could focus on finding an optimal approach to finance climate change adaptation and avoid a sudden economic collapse of agriculture. This study should be based on agricultural economics.

The second research opportunity identified is the analysis and recommendation of methods to increase stakeholders' awareness to climate change and its effect on the local communities. Another observation of the analysis presented in Chapter 2 is that farmers do perceive that the climate is changing but they do not perceive climate change as an imminent threat. As previously mentioned, there is substantial scientific evidence suggesting that adequate climate perceptions encourage climate change adaptation. Stakeholders who hold incorrect climate perceptions and who do not perceive the risk that climate change represents to them, do not actively seek to adapt. Therefore, better science communication and more access to scientific research is needed. The new study could focus on methods to increase climate change awareness and on ways to deliver climate change information according to the stakeholders' needs and preferences.

The third research opportunity is to analyze and suggest methods to promote and implement better soil management practices. During the analysis presented in Chapter 2, many of the stakeholders mentioned that the current crop rotation and the agricultural practices are not favorable to promote humification and good soil health. The results of the analysis performed in Chapter 4 highlighted the importance of humification to reduce IWD. Humification and living soils have also additional advantages from which farmers could benefit. However, it is still unclear how farmers in Uelzen and Seewinkel could increase the quality of their soils, as humification is strongly linked to crop rotation. Further research could focus on the development and implementation of ideal agricultural practices for the region. These practices should promote humification, be economically feasible and should neither increase IWD nor emissions.

The fourth research opportunity is to develop and suggest a new crop rotation to substitute the current one. This research opportunity is closely linked to the third, as crop rotation has a strong influence on the soil. The results of the analysis performed in Chapter 2 showed that the crop rotation in NELS has not been modified as the whole system is built around those three cash crops. The results of the analysis performed in Chapter 3 and Chapter 4 showed that changing crops is the best adaptation measure to reduce IWD and increase the local water resources. However, changing the crop rotation is a difficult issue as it could imply that some local businesses, like the sugar refinery in Uelzen, might become bankrupt. Therefore, developing a crop rotation, which could benefit all parties and still have additional benefits such as promoting humification and reduced IWD, would be ideal to support local climate change adaptation. The study to develop a new crop rotation should therefore have a strong fundament in agricultural economics.

The fifth research opportunity is to suggest changes and updates to the water management strategy, so it considers the effects of climate change. During the analysis made in Chapter 2, it was observed that the local water management strategy does not consider the effects of climate change. Traditionally, water management laws are based on historical data. Thus, they consider a static system with range for seasonal variation and abnormal weather events. However, due to climate change, the hydrological system cannot and should not be considered to be stable. Therefore, the local water management strategy should be adapted to consider the changes caused by climate change on water availability and the increase in extreme weather events such as droughts. Because of the nature of the task, the new research should have a strong basis on environmental law and water management.