Estimating current and possible future irrigation water requirements

An approach for the Rhine basin during the growing season in periods of drought

Master thesis

Foekje van Schoot

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Colophon

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Image on cover page	Farmland in France being irrigated (Flower, 2021)

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Deltares

Preface

When starting this research on the estimation of current and possible future irrigation water requirements by the agricultural sector in the Rhine basin, I hit on the origin of the name 'Rhine' quite soon. It was in a sentence, said to have been spoken by Heraclitus and which I would like to start this preface with:

Σωκράτης·
λέγει που Ἡράκλειτος ὅτι '**πάντα χωρεῖ** καὶ οὐδὲν μένει,' καὶ ποταμοῦ ῥοῇ ἀπεικάζων τὰ ὄντα λέγει ὡς 'δὶς ἐς τὸν αὐτὸν ποταμὸν οὐκ ἂν ἐμβαίης.'

Socrates:
Heraclitus says, you know, that **all things move** and nothing remains still, and he likens the universe to the current of a river, saying that you cannot step twice into the same stream.

Plato, in Cratylus (402a)

Nothing remains still, and all things move (ῥεῖν). So, the Rhine is flowing in its name. First of all, I think this is a nice little-known fact, second of all, it describes the process of graduating perfectly. This whole thesis journey was one of continuous movement: writing, modelling, evaluating, reflecting and repeating all these steps again. However, it was a pleasant journey which I enjoyed a lot most of the time, because I learned many new things and have had very valuable help. Therefore I would like to thank some people.

First, I would like to thank Maarten for his guidance, patience and the way he gave feedback, it was always in such a way that I got in the right direction, but still had to figure out by myself. Secondly, I would like to thank Rick for all comments made on my draft versions; it was straightforward, honest and gave me a lot of insights in my writing style. Thirdly, I would like to thank Frederiek for the motivating weekly meetings, the willingness to always email me very quickly and for arranging things within Deltares. I would also like to thank Wil, for guiding me through RiBaSIM and helping me out with errors even during the weekends.

Also, many thanks to André, Gidde, Steven and Bart for their library support, coffee breaks and feedback.

Foekje van Schoot

Enschede, February 2021

Summary

The year 2018 turned out to be an extremely dry year in the Rhine basin (Wilkes and Parkin, 2020), with the same trend continuing in the years 2019 and 2020 during the growing season or summer period (KNMI, 2020a). This has led to alarming low water levels in main rivers such as the Rhine, which has negatively impacted sectors dependent on these water flows. The agricultural sector, which is the largest water consuming sector in the world, is one of these sectors. Especially in dry years, crops are dependent on irrigation water from surface water (e.g. rivers). The goal of this study is to estimate the current and possible future irrigation water requirements of the agricultural sector in the Rhine basin and consequently, its impacts on the Rhine river flow during growing seasons. With the help of the Aqua21 water footprint accounting model and the Delft-Agri water demand and allocation model, water requirements are quantified, compared with historic data for validation, and assessed for future scenarios.

Since irrigation water is mostly applied during dry years, these years are considered in this study. The four most important irrigated crops in terms of irrigation water use (m^3) – sugar beet, potatoes, maize and oats - are used for the estimation of current and future water requirements.

The Delft-Agri model can calculate the gross water requirement (m^3) for any time at any location, and the model package RiBaSIM is able to show the river discharge (m^3/s) of various stations. In this study, agricultural input data for the Delft-Agri model for the Rhine basin were taken from Aqua21. Therefore, first the model performance of Aqua21 is tested against small scale (NUTS-1 level) validation data. The model turns out to perform good on the variables production (tonne) and yield (tonne/ha) for both average, as well as dry years. Afterwards, the performance of the Delft-Agri model is tested against Aqua21 results. The model turns out to perform good on the net water requirement (m^3) variable. However, the Delft-Agri model for the Rhine basin does not account for drought damage in the production (tonne) variable. The performance of the river discharge (m^3/s) variable is rather low for low flows, which limits the analysis on estimating the impact of changing river flow under various scenarios.

To scope possible future irrigation water use in the Rhine basin, four scenarios are designed with the help of the story-and-simulation approach (Alcamo, 2001): *modest global warming – intensive agriculture, modest global warming – sustainable agriculture, much global warming – intensive agriculture, much global warming – sustainable agriculture.*

This study shows that the current irrigation water requirement of the agricultural sector in the Rhine basin during the growing season in periods of drought can go up to $9.4*10^7$ m^3/month. The possible

future irrigation water requirement of the agricultural sector in the Rhine basin during the growing season in periods of drought varies per scenario. For the *intensive agricultural* scenarios an increase of 96% (*modest global warming*) to 130% (*much global warming*) can be expected during the growing season for the year 2050. The *sustainable agriculture* scenarios show an increase of 12% (*modest global warming*) to 33% (under *much global warming*) compared to the current scenario.

The impact of the irrigation water requirement (m^3) on river discharge ($m^{3/}s$) is rather low: changes in river flow relative to the reference scenario remain below 1% for both the main river as the side rivers. This estimation only considers the impact of the scenarios, not the decrease in river flow due to climate change.

This study has sought a methodology to estimate the current and future irrigation water requirement of the Rhine basin. While this study has given new insights, some challenges still remain to be solved in future research. It is recommended to expand the Delft-Agri model with a dynamic crop plan, so crop ratios can be set per year, resulting in more precise water requirement estimations per sub-basin. The possibility to insert dynamic potential crop yield (Y_m) values would also increase the model's accuracy on yield estimations. Furthermore, the collection and use of irrigation data on small scales (NUTS-1 level) would improve the model results of both Aqua21 and Delft-Agri. Especially when the sub-basin resolution of the Delft-Agri model is increased.

Samenvatting

Het jaar 2018 was een extreem droog jaar in het Rijnstroomgebied (Wilkes and Parkin, 2020), dit was ook te zien in de opeenvolgende jaren, tijdens het groeiseizoen of de zomerperiode (KNMI, 2020a). Dit heeft geleid tot alarmerende lage waterpeilen in grote rivieren zoals de Rijn, met negatieve gevolgen voor sectoren die afhankelijk zijn van water uit het stroomgebied. De landbouwsector, die de grootste watergebruiker ter wereld is, is een van deze sectoren. Vooral in droge jaren zijn gewassen afhankelijk van irrigatiewater uit oppervlaktewater (zoals rivieren). Het doel van deze studie is een inschatting te maken van de huidige en mogelijke toekomstige irrigatiewaterbehoefte van de agrarische sector in het Rijnstroomgebied en daarmee de effecten op de rivierafvoer van de Rijn te bepalen tijdens het groeiseizoen. Met behulp van het Aqua21 water footprint accounting model en het Delft-Agri watervraag en waterallocatie model wordt de waterbehoefte gekwantificeerd zodat verschillende scenario's vergeleken kunnen worden.

Het onderzoek richt zich op droge jaren, aangezien in deze jaren het meeste irrigatiewater wordt gevraagd. De vier grootste geïrrigeerde gewassen wat betreft irrigatiewatergebruik (m^3) - suikerbieten, aardappelen, maïs en haver - worden gebruikt voor de schatting van de huidige en toekomstige waterbehoefte.

Het Delft-Agri model kan op elk moment en op elke locatie de bruto waterbehoefte (m^3) berekenen en kan ook de rivierafvoer (m^3/s) van verschillende stations weergeven. In dit onderzoek is agriculturele input data voor het Delft-Agri model van het Rijnbasin genomen uit het Aqua21 model. Daarom wordt eerst de modelprestatie van Aqua21 getest tegen NUTS-1 level validatie data. Dit model blijkt goed te presteren voor de variabelen productie (ton) en opbrengst (ton/ha) voor zowel gemiddelde als droge jaren. Daarna wordt de prestatie van het Delft-Agri-model getest tegen de Aqua21 resultaten. Delft-Agri blijkt goed te presteren op de variabele netto waterbehoefte (m^3). Delft-Agri houdt, voor het Rijnbasin, echter geen rekening met droogteschade in de productie (ton) variabele. De prestatie van de variabele rivierafvoer (m^3/s) is vrij laag, waardoor de analyse van de impact van veranderende rivierafvoer onder verschillende scenario's beperkt is.

Met behulp van de verhaal-en-simulatiebenadering zijn er vier scenario's ontworpen (Alcamo, 2001): *modest global warming – intensive agriculture, modest global warming – sustainable agriculture, much global warming – intensive agriculture, much global warming – sustainable agriculture.*

Uit deze studie blijkt dat de huidige irrigatiewaterbehoefte van de landbouwsector in het Rijnstroomgebied tijdens het groeiseizoen in periodes van droogte kan oplopen tot $9{,}4 \times 10^7$ m^3/maand. De mogelijke toekomstige irrigatiewaterbehoefte van de agrarische sector in het Rijnstroomgebied

tijdens het groeiseizoen in periodes van droogte verschilt per scenario. Voor de intensieve landbouwscenario's kan dit tijdens het groeiseizoen in 2050 stijgen met 96% ten opzichte van de huidige situatie (weinig opwarming van de aarde) tot 130% (veel opwarming van de aarde). De scenario's voor duurzame landbouw laten een stijging zien van 12% (weinig opwarming van de aarde) tot 33% (veel opwarming van de aarde) in vergelijking met het huidige scenario.

De impact van de irrigatiewaterbehoefte (m^3) op de rivierafvoer (m^3/s) is vrij laag: veranderingen in rivierafvoer ten opzichte van het referentiescenario bedragen niet meer dan 1% voor zowel de hoofd- als zijrivieren. Deze berekening houdt echter alleen rekening met de invloed van de scenario's, en neemt de afname van het waterpeil in de rivier door klimaatverandering niet mee.

In deze studie is gezocht naar een methodiek om de huidige en toekomstige irrigatiewaterbehoefte van het Rijnstroomgebied in te schatten. Hoewel deze studie nieuwe inzichten heeft opgeleverd, zijn er nog wat uitdagingen voor toekomstig onderzoek. Aanbevolen wordt om het Delft-Agri model uit te breiden met een dynamisch teeltplan, zodat gewasverhoudingen per jaar kunnen worden ingesteld. Ook de mogelijkheid om dynamische potentiële gewasopbrengsten (Y_m) in te voeren zou meer modelnauwkeurigheid toevoegen. Bovendien zou het verzamelen en registreren van irrigatiegegevens op lagere schaal (NUTS-1-niveau) de modelresultaten van zowel Aqua21 als Delft-Agri verbeteren. Vooral wanneer de sub-basin resolutie van Delft-Agri zal toenemen.

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List of abbreviations

BWF	Blue Water Footprint
CCM	Corn Cob Mix
CHR	The international Commission for the Hydrology of the Rhine basin
FAO	Food and Agriculture Organization
HYMOG	Hydrological Modelling Basis in the Rhine Basin
IKA	Interkwartielafstand (Interquartile range)
IKSR/ICPR	Internationale Kommission zum Schutz des Rheins/ International Commission for the Protection of the Rhine
IPCC	Intergovernmental Panel on Climate Change
NSE	Nash-Sutcliffe Efficiency
r	Correlation
RVE	Relative Volume Error
SAS	Story-and-Simulation
SES	Socio-economic scenario
WWC	World Water Commission

1. Introduction

1.1 Background

The year 2018 turned out to be an extremely dry year in the Rhine basin (Wilkes and Parkin, 2020), with the same trend continuing in the years 2019 and 2020, during the growing season or summer period (KNMI, 2020a). Water levels in main rivers, such as the Rhine are depressing (Wilkes and Parkin, 2020). This leads to negative impacts for inland shipping, which given its vital role in connecting the port of Rotterdam to inland European markets, can severely impact national economies (Te Linde et al., 2011).

There are more sectors in the basin dependent on water of the basin, such as the private sector for domestic water use, the industrial sector for industrial water use, the energy production sector for cooling water use, the mining sector for pumping water discharge and lake refilling, and the agricultural sector for irrigation water use (Deltares, 2019). The agricultural sector has a large water demand, because crops cannot grow without water. From a global perspective, the agricultural sector is the highest water consuming sector: 92% of the water footprint of humanity lies within the agricultural sector (Hoekstra and Mekonnen, 2012). Currently, 40% of the global yields are harvested on irrigated areas (FAO, 2014). Irrigated areas almost doubled over the last 50 years globally (Neumann et al., 2011 in Meier et al., 2018). Due to climate change a future expansion of irrigated areas is expected (Neumann et al. 2011 in Meier et al., 2018). On the regional scale this can have a large influence on the ratio rainfed versus irrigated crops.

A number of climate studies have shown that dry summers are more likely to occur in the future, which are caused by higher temperatures and air pressures (KNMI, 2020c) (Lenderink and Beersma, 2015). Consequently, for the Rhine basin, an increase in irrigated area and a related increase in irrigation water consumption is expected.

During the 16th Rhine ministers conference (2020) by the IKSR (Internationale Kommission zum Schutz des Rheins or ICPR) the focus was on drought and low water events. During the conference the importance of further investigating low water management became clear. The IKSR stressed that "research about future water availability in the Rhine catchment for the year 2050 should be executed" and that "creating awareness among water users about water availability is necessary" (IKSR, 2020). In order to answer questions on fresh water availability in the Rhine basin, the water requirement of the sectors active in the Rhine basin has to be estimated.

The study Rhine001 by Deltares (Deltares, 2019) commissioned by the CHR (International Commission for the Hydrology of the Rhine basin), was a first attempt to indicate the influence of several sectors on the discharge of the Rhine basin. Water consumption by the agricultural sector was specified to irrigation water use. The irrigation water use was based on irrigated area of cereals and other cropland multiplied by the average irrigation in mm/month. Data on irrigated areas was derived from Eurostat total area data (Eurostat, 2019), and the average irrigation in mm/month was based on expert judgement. Both variables are educated conjectures and were first attempts, they can be considered as not very reliable (Deltares, 2019).

1.2 Research gap

Currently, there is no reliable estimate of the current and possible future irrigation water requirements of the agricultural sector in the Rhine basin and consequently, the impacts on river flow of the Rhine during the growing season are uncertain. Second, no specific subdivision has been made in the type of irrigated crop. Third, the role of climate change on the possible irrigation water requirement of the agricultural sector in the future has not been estimated.

1.3 Research objective

The objective of this study is to estimate the current and possible future irrigation water requirements of the agricultural sector in the Rhine basin and its impacts on river flow of the Rhine during the growing season.

1.4 Scope

To estimate the irrigation water requirements of the agricultural sector, this study makes use of two models. The two models are totally different in its sort. One, Aqua21, is a water footprint accounting model that makes use of crop models as subroutines, whereas the second model, Delft-Agri, is the agricultural module within the water demand and allocation model package RiBaSIM (River Basin Simulation). Aqua21 is chosen since it is a crop growth (phenological) model, this type of model computes the water use by the crop per time step. Aqua21 uses the state-of-the-art AquaCrop model. The AquaCrop model performs as good as any other crop growth engine (Adam et al., 2011 in Hogeboom et al., 2020). Delft-Agri, which is developed by Deltares (Deltares, 2020b), is chosen since it is a water demand and allocation model and because it considers many different variables, besides it is user-friendly and together with the industrial and domestical water demand, it gives a complete picture in RiBaSIM of water demand and allocation in the Rhine basin (Van der Krogt and Boccalon, 2013).

The study focuses on dry years, since irrigation water is applied mostly during these years, because of an increase in evapotranspiration and a decrease in rainfall (KNMI, 2020c). During dry years there might be negative impacts for the agricultural sector and river flow in the river Rhine. Besides, in climate scenarios for the Rhine, the scenarios in which dry summers appear are expected the most (KNMI, 2020c) (Lenderink and Beersma, 2015).

The geographical scope of this research is the Rhine basin (Figure 1). The basin is formed by the river Rhine which originates in Switzerland, forms part of the boundary between France and Germany and continues flowing through Germany before entering the Netherlands at Lobith. The basin is in its entirety 185.000 km^2 and has been subdivided into nine sub-basins. The division is based on geographical characteristics and is invented by the IKSR to reduce the complexity and size of the basin when designing management plans (IKSR-CIPR-ICBR, 2000). The basin itself covers the countries Switzerland, Italy, Liechtenstein, Austria, Belgium, Luxembourg, Germany, France and the Netherlands. In this study, datasets of the Aqua21 model are used such as the harvested areas and yield datasets by Monfreda et al. (2008) and Portmann et al. (2010), which have a spatial resolution of 5 x 5 arc minutes.

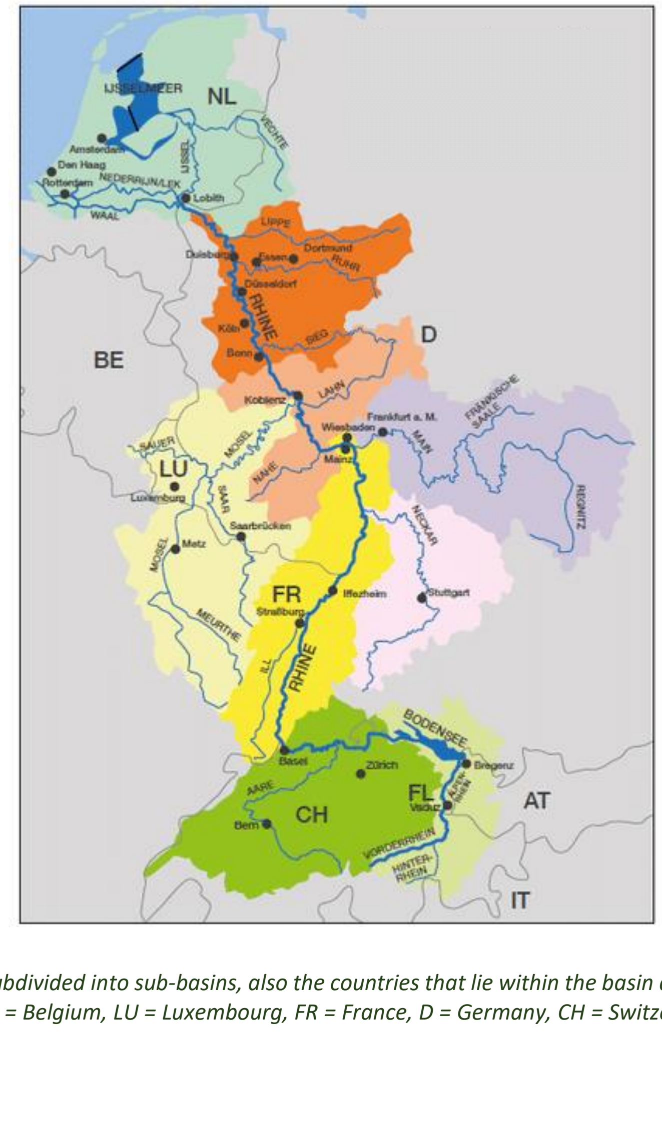

Figure 1: The Rhine basin subdivided into sub-basins, also the countries that lie within the basin are depicted (Schmid-Breton, 2016) *NL = Netherlands, BE = Belgium, LU = Luxembourg, FR = France, D = Germany, CH = Switzerland, FL = Liechtenstein, AT = Austria, IT = Italy.*

The temporal scope of this research is the period 1980-2010 to estimate the current irrigation water requirement, because for this period data is available for both models that are used in this research. To estimate the possible future irrigation water requirement, scenarios for the year 2050 are designed, because for this year research about water availability should be executed according to the Rijnministersconferentie (2020). The temporal resolution is a year, reflecting the typical growing season of crops.

In terms of crops, the crops responsible for the majority (>95%) of irrigation water demand in the basin are included in the research, which are sugar beet, oats, potatoes and maize (estimated with the Aqua21 model (Hogeboom et al., 2020). Appendix A shows how these crops were determined.

1.5 Research questions

The main question of this research is as follows:

'What are current and possible future irrigation water requirements of the agricultural sector in the Rhine basin during the growing season in periods of drought and what are the impacts of this water demand on river flow?'

To answer the main question, two models are used: Aqua21 and Delft-Agri. The sub questions that are formulated to answer the main research question read:

1. What are the model differences in terms of input variables, processes and definitions?
2. What is the performance of both models during average years?
3. What is the performance of both models during dry years?
4. Which agricultural scenarios are plausible for the future in the context of increasing drought?

1.6 Outline

First, the two models used in this study are introduced in chapter 2: Aqua21 and Delft-Agri. The chapter provides general model descriptions for both models and also the model applications in this particular study. Chapter 2 helps to better understand the methodology on the models as described in chapter 3. Chapter 3, the methodology chapter, elaborates on the followed research steps in this study. The chapter is divided into four parts, each part representing a research sub-question. Chapter 4 provides the results for each sub question and has also been divided in four parts: each part representing a sub-question. Chapter 5 provides a general discussion on the meaning and limitations of the results. In chapter 6, the research is concluded with answering the main research question. Finally, in chapter 7 recommendations for further research and implementations of the results in the Rhine RiBaSIM model are given.

2. Models

Before diving into the methodology used to answer the research questions, a brief overview of the Aqua21 and Delft-Agri model is given in order to understand their structure and application.

2.1 The Aqua21 model

2.1.1 General model description

Aqua21 is a water footprint accounting model developed to compute green and blue water footprints (the water footprint concept is explained in Appendix B). The model follows a grid-based approach with a spatial resolution of 5 x 5 arc minutes (Hogeboom et al., 2020). For each grid cell blue and green water footprints can be estimated for crop production. Grid cells could then be aggregated to higher spatial levels such as sub-basins or river basins.

The Aqua21 model uses a sophisticated soil water balance – crop growth simulation model: AquaCrop, developed by the FAO (Raes, 2016). Water footprint calculations have been done for each month of each year for the period 1961-2010. This makes it possible to do both intra-annual and inter-annual comparisons.

AquaCrop is a water productivity simulation model that can be used for both herbaceous crops, as well as tree crops (FAO, 2020a). The model translates evapotranspiration into biomass production and yields (Raes et al., 2018) (a flowchart of the processes within the AquaCrop model is given in Appendix C.1). Yield calculations are done in four steps which are explained in Appendix C.2. The required input variables of the AquaCrop model are explained in Appendix C.3. In Aqua21 yields (tonne/ha) have been scaled to national statistics, as well as the harvested areas (ha) (Hogeboom et al., 2020).

The Aqua21 model is particularly useful for situations in which water is a key limiting factor in crop production. Situations that can be thought of are deficit irrigation or crop management practices, such as making use of mulches. Aqua21 also is useful for comparison studies (historical vs future weather conditions or attainable vs actual yields), it can also be used as a supportive tool for decision-making on water allocations and other policies (FAO, 2020a).

2.1.2 Model application

This study focuses on the Rhine basin, therefore a sub-selection of this geographical region is made. Within this region, grid-level outputs are aggregated to sub-basin level spatial scales. Figure 2 shows where the irrigated crops considered in this study are located (reference year 2000), according to the Aqua21 model (Hogeboom et al., 2020). Per grid cell, the irrigated crop with the largest irrigated harvested area is depicted. That means that in grid cells where maize is irrigated, also sugar beet, potatoes or oats might be irrigated.

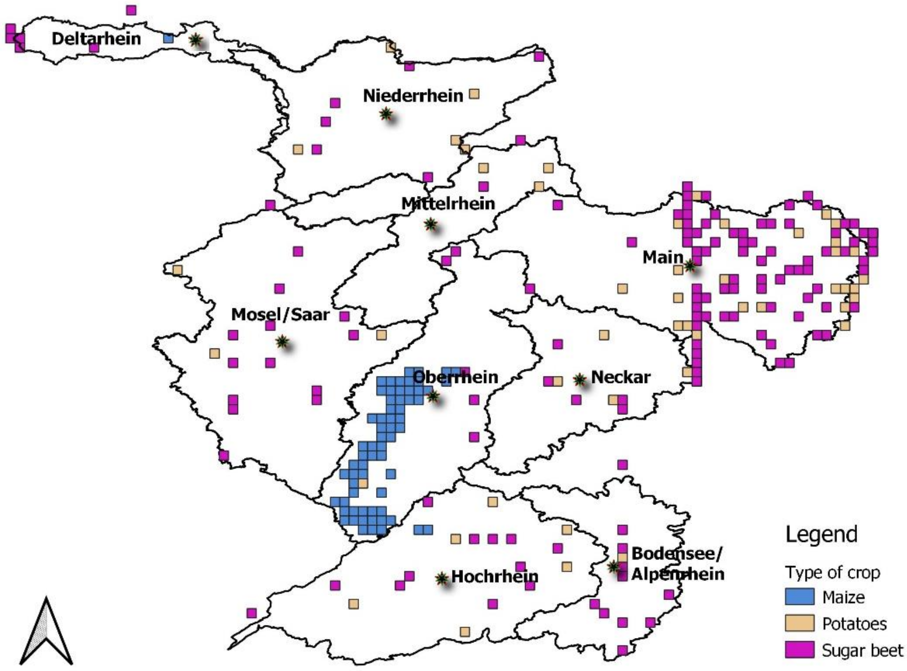

Figure 2: Schematization of the Rhine basin in 5 x 5 arc minutes by the Aqua21 model. The irrigated harvested areas for the year 2000 for the selected crops of this study are shown. Per cell, the crop with the largest irrigated harvested area is depicted.

2.2 The Delft-Agri model

2.2.1 General model description

Concerning the water demand and allocation model in this research, five model routines/packages need to be introduced: RiBaSIM, Wflow, Delft-Agri, CROPWAT and Cropper.

RiBaSIM is the model package, which was developed by Deltares in 1985, and is a tool to analyse the behaviour of river basins under various hydrological conditions (Van der Krogt, 2009). The model package can link the water inputs at numerous locations with water users in the catchment (Van der Krogt, 2009). Also, the model package includes routing (various procedures are possible: Manning, time-delayed Puls method, Laurenson non-linear lag and route methods, etc.), so water distribution across the basin can be followed. It indicates when and where conflicts might occur between water users and it can show the effect of potential measures to improve water supply, which helps to indicate the agriculture production costs and yields. RiBaSIM takes into account discharges form several modules, such as agriculture and industry, and so it can provide detailed simulations of water balances within a basin. Schematizations of river basins are made in RiBaSIM with the help of nodes and branches which form a network superimposed over a river basin map. The nodes represent reservoirs, pumps, water users, intake structures and so forth, the branches represent the water streams between the nodes. Schematization can be done on every scale, as long as there is sufficient corresponding information (Van der Krogt, 2008). Concerning the times series: simulation is mostly done for multiple years, to include the occurrence of wet and dry periods (Van der Krogt, 2009). Time steps can be determined per simulation, in each time step water demand is determined, which leads to water releases in other parts of the system (from reservoirs, lakes, pumping stations and so on) (for an overview of the phases of each time step, see Appendix D.1). During the simulation, the water is allocated to the users according to the set targets (more explanation on the source priorities can be found in Appendix D.1). It is possible to track the water's origin and its residence time at any location of the basin at any time within the simulation period. Groundwater is modelled as a separate source with its own characteristics (Van der Krogt, 2008).

Wflow is a distributed rainfall-runoff model and delivers the hydrological input data for the RiBaSIM model. It calculates the runoff at any given point at a given time step, based on meteorological input data and physical parameters (Van der Krogt et al., 2021). Wflow needs static and dynamic data in order to calculate the runoff. Static data include: a digital elevation model, a river network, a land-use map, a soil map, and physical parameters defining the properties of different soil types, land-use types and sub-basins. Dynamic data include: discharge data (for calibration and validation) and meteorological data (precipitation, temperature, evapotranspiration) (Van der Krogt et al., 2021).

Delft-Agri is one of the modules within the RiBaSIM model package, it represents the agricultural sector in the river basin. Delft-Agri is represented in the model by the 'irrigation agriculture' nodes. Four different types of irrigation nodes exist: (1) Fixed irrigation node; (2) Variable irrigation node; (3) Advanced irrigation node; (4) Groundwater district node. The nodes are further explained in Appendix D.2. Delft-Agri simulates the root-zone of the crops and also calculates the soil moisture per time step. It specifies the daily output on field level and is based on CROPWAT calculation methods (Van der Krogt and Boccalon, 2013).

CROPWAT calculation methods are based on two FAO publications of the Irrigation and Drainage Series, namely number 56 'Crop evapotranspiration – guidelines for computing crop water requirements' and number 33 'Yield response to water' (Doorenbos and Kassam, 1979; FAO, 2021). With these calculation methods the crop water requirement and irrigation water requirements can be calculated (FAO, 2021).

Cropper is an interactive graphical crop plan editor, in which the cropping pattern can be defined. Variables such as planting time step, area, percolation, growing period are needed as input. Cropper then calculates, with CROPWAT calculation methods (Van der Krogt, personal communication, July 13 2020), the water demand per time step which is used as input for Delft-Agri. Appendix D.3 shows a crop-time diagram and associated water balances for planned cultivations.

2.2.2 Model application

A RiBaSIM application is available for the Rhine basin, which has a schematization including hydrological input data from Wflow. Wflow already accounted the water consumption of rainfed crops in the rainfall-runoff time series based on land use data from the CORINE landcover map (European Environment Agency, 2018) (variables such as Manning roughness coefficient an the rooting depth are used) and on soil data from the SoilGrids250m dataset in order to derive soil variables (Hengl et al., 2017). Also, a digital elevation model based on Merit-Hydro is used to derive the slope and river network of the Rhine (Yamazaki et al., 2019). However, agricultural input data has not been included in the Rhine schematization yet, therefore agricultural input data for the Delft-Agri model is collected in this research.

The schematization that has been made already, is made with nodes and branches, which form a network over the river basin map. The type of irrigation node that is used for the Rhine basin is the 'advanced irrigation node'. This type of node accounts for agricultural water demand, allocation, crop yield and production costs (Van der Krogt, 2008), as is required to estimate the current and possible future irrigation water requirements of the agricultural sector in the Rhine basin during the growing season in periods of drought.

The schematization of the advanced irrigation nodes in the Rhine river basin in RiBaSIM is depicted in Figure 3. Ten irrigation nodes are distinguished (Figure 3) (Table 1) and are based on the sub-basin division (see Appendix E for the sub-basin division of the Rhine), which is the spatial resolution of the Rhine RiBaSIM model of this study. However, in the sub-basin Deltarhein an extra subdivision is made: Rivierengebied and Benedenrivierengebied. This division is made by Deltares to easily implement measures later on in the RiBaSIM model based on Delta decisions (Delta Programma Zoetwater) (see Appendix E) (Ter Maat and Vat, 2015). The temporal resolution of the Rhine RiBaSIM model of this study is a ten day time period, that means that a year is subdivided into 36 periods (Deltares, 2020b).

In the Rhine RiBaSIM model no groundwater reservoir nodes are implemented. This means that the demand nodes, such as the advanced irrigation node and the public water supply node, cannot be supplied by groundwater but just by surface water in the model.

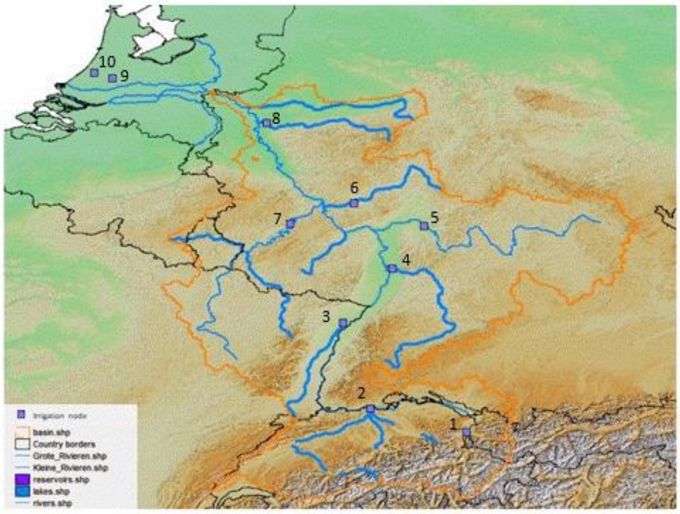

Figure 3: Schematization of the advanced irrigation nodes within the Rhine basin as presented in the RiBaSIM model (Deltares, 2020b)

Table 1: Naming of the advanced irrigation nodes in the Rhine RiBaSIM model (Deltares, 2020b)*, numbers refer to Figure 3*

Advanced irrigation node number	**Advanced irrigation node name**
1	Bodensee/Alpenrhein
2	Hochrhein
3	Oberrhein
4	Neckar
5	Main
6	Mittelrhein
7	Mosel/Saar
8	Niederrhein
9	Rivierengebied
10	Benedenrivierengebied

3. Methodology

This chapter is composed of four sections. Every section treats the methodology of a research sub-question. The first section of this chapter explains how both models are compared. Before this comparison can be made, Delft-Agri needs to be initialized for this research, so a description on the model set-up is given as well. The second section explains the methodology to estimate the model performance of both models in average years. The section focuses on the validation data used and the methods of validation which are both descriptive as well as statistical. The third section explains the methodology to estimate the model performance of both models in dry years. First, the dry years are defined and then validation methods are explained. Finally, in the last section, the methodology on how to develop scenarios is explained.

3.1 Model comparison

Whereas in chapter 2 a general overview of the models and their application for this study are given, chapter 3 further investigates the model details in terms of input, processes and definitions. A necessary prerequisite to analyse model differences, is the set-up of the Delft-Agri model. For the Aqua21 model this was already done: data for the variables was available and already implemented, but the Delft-Agri model was not set-up yet. As a result, the model set-up of Delft-Agri is explained first, followed by the method of comparison.

3.1.1 Model set-up

As mentioned in section 2.2.2 the RiBaSIM application for the Rhine basin has a schematization with advanced irrigation nodes. The hydrological input data for these nodes was already available and is shown in Table 4. In contrast, crop and crop production data was not readily available. Therefore, data to determine the actual crop plan, crop characteristics, soil characteristics, topography and lay-out of the irrigation area, and data on the operation and irrigation water management are collected in this study. Data is collected from literature, experts' knowledge, and from the Aqua21 dataset.

The actual crop plan has been set-up in Delft-Agri with the year 2000 as the reference year. Where the Aqua21 model has a different crop plan every year, the Delft-Agri model can just have one crop plan per scenario. That means that for the period 1980-2010 the same crop plan is used for every year. For most of the selected crops the harvested area is not heavily changing over the years, except for oats (see Appendix A). The Delft-Agri design of a crop plan includes the harvested area (ha) per crop type which has to be implemented per sub-basin. First, the harvested area for the selected crops has been selected for the Rhine basin, for the year 2000 from the Aqua21 dataset (Hogeboom et al., 2020). This is done for both irrigated crops (so irrigated harvested area) as for irrigated and rainfed crops together (so irrigated and rainfed harvested area together). In case there are multiple harvests of the same crop on the same field in a season/year, the harvested areas are summed. These harvested area crop plans are implemented in QGIS, together with a map that shows the sub-basins in the Rhine basin (Deltares, 2020a). Subsequently, joins are made between those layers, and so the harvested area is extracted for the year 2000, per type of crop, per sub-basin/ irrigation node for the four irrigated crops (Table 2), as well as for the four irrigated and rainfed crops together (Table 3).

Table 2: Crop plan implemented in Delft-Agri based on the Aqua21 dataset for the reference year 2000. The irrigated harvested area per crop per sub-basin is given in ha.

Crop areas (ha) **Crop type** **Subbasin name**	**Potatoes**	**Sugarbeet**	**Oats**	**Maize**
1. Bodensee/Alpenrhein	117	29	13	19
2. Hochrhein	878	704	315	358
3. Oberrhein	4784	9037	1542	7591
4. Neckar	371	1505	126	18
5. Main	1722	7662	119	37
6. Mittelrhein	576	1478	134	17
7. Niederrhein	2556	6096	0	9
8. Mosel/Saar	28	8	0	0
9. Rivierengebied	13	0	0	2
10. Benedenrivierengebied	0	0	0	0

Table 3: Crop plan implemented in Delft-Agri based on the Aqua21 dataset for the reference year 2000 (Hogeboom *et al.*, 2020)*. The total harvested area for both irrigated and rainfed crops per sub-basin is given in ha.*

Crop areas (ha) **Crop type** **Subbasin name**	**Potatoes**	**Sugarbeet**	**Oats**	**Maize**
1. Bodensee/Alpenrhein	11221	13639	4480	18215
2. Hochrhein	9791	26826	8532	90453
3. Oberrhein	3057	15293	8104	14384
4. Neckar	10108	41886	18992	24755
5. Main	4319	12124	6232	7992
6. Mittelrhein	16498	37374	9422	19655
7. Niederrhein	2200	5000	11000	18000
8. Mosel/Saar	4017	4512	3301	9755

9. Rivierengebied	4114	2426	0	738
10. Benedenrivierengebied	2500	5000	0	1000

The other variables that are collected and used in this study are listed in Table 4. The variable name, unit, interpretation and the source of the variable for this study are shown. Variables for the crops, as well as variables for crop production and hydrological variables are shown.

Besides these, there are more variables in the RiBaSIM model, which include those for flood basin crops. Since flood basin crops (such as rice or paddy) do not grow in the Rhine basin, only dry land crops and their variables are considered. It is furthermore noted that some hydrological variables are not considered in the Rhine basin application of the RiBaSIM model, mainly due to a lack of data. Hydrological variables that are not considered are: loss flow, general district discharge, monitored flow data, dependable river flow, expected inflow and potential evapotranspiration for the Sacramento model (E-mail correspondence with Sperna Weiland and Van der Krogt, October 8, 2020).

Table 4: List of variables of the Delft-Agri model, the interpretation of the variables is included as well as the source of the variable for this research.

	Variable	Unit	Interpretation	Source
Crop	Rootzone depth	mm	Depth of the modelled soil layer, maximum root zone depth	Potatoes and sugar beet (Metselaar et al., 2009); Maize and oats (Fan et al., 2016); Other (apples) (Tanasescu and Paltineanu, 2004)
	Crop factor		Kc-values for each timestep and crop. Initial, mid and end Kc values are given, the development and degradation stages are linearly interpolated.	From the Aqua21 database (Hogeboom et al., 2020)
	Ky		Yield response ratio to water at different stages of plant growth. Per time step per crop	Based on Mekonnen and Hoekstra (2011a) who refer to FAO Drainage and Irrigation Paper 33 (Doorenbos and Kassam, 1979).
Crop Production	Planting period (plt. Per)	10 day periods	Planting period to cover the whole cultivated area with the crop (number of time steps to plant everything)	Expert knowledge (Van der Krogt, personal communication, October 27 2020)
	Ym	Tonne/ha	Potential yield: 6 year average (1997-2002) for Germany	(Destatis, 2020b)
	Crop plan	ha	Harvested area per crop per sub-basin, as shown in Table 2 and Table 3	Aqua21 dataset (Hogeboom et al., 2020)
	Growing season (grow.seas)	10 day periods	Length of the growing season excluding land preparation (per time step)	From the Aqua21 database, data as used by (Allen et al., 1998; Mekonnen and Hoekstra, 2011)
	Field buffer storage (FldBfrSt)	mm	Field buffer storage for each crop per time step, mm above the desired water level or soil moisture. 4% of the rootzone (value between field capacity and saturation capacity).	Potatoes and sugar beet (Metselaar et al., 2009); Maize and oats (Fan et al., 2016); Other (apples) (Tanasescu and Paltineanu, 2004)
	Irrigation Practice (Irrpract)		Determine per time step if there is irrigation (1) or not (0): just irrigated crops (1) are considered in this research.	
Hydrology	Actual inflow	mm/day	Inflow time series per sub-basin for the Rhine. Data of 91 stations.	Wflow model Deltares

	Actual rainfall	mm/day	Actual rainfall time series per reservoir node and sub-basin for the Rhine. Data of 157 stations.	ERA5 re-analysis ECMWF (via Wflow to Ribasim7) (ECMWF, 2019)
	Open water evaporation	mm/day	Open water evaporation time series per reservoir node for the Rhine. Data of 66 stations.	Potential evaporation calculated from ERA5 (via Wflow to Ribasim7 used for reservoir evaporation)
	Dependable rainfall	mm/day	Annual time series of the dependable rainfall, based on actual rainfall. Data of 157 stations.	Computation of actual rainfall time series into dependable rainfall time series is done by the RiBaSIM program GenDepSer (generate dependable series)
	Reference evapotranspiration	mm/day	Calculated per sub-basin; for every time step the average of 30 years is taken (1980-2010)	Calculations based on ERA5 dataset

3.1.2 Method for comparison

After the model set-up of Delft-Agri, both Aqua21 and Delft-Agri have model input. From then, further investigation on the model differences in terms of input, processes and definitions has been done. Scientific papers were studied, for Delft-Agri the search term 'CROPWAT' was used, since Delft-Agri makes use of this model. Relevant manuals were consulted to gain insights into model input, processes and definitions. For the Aqua21 model manuals of AquaCrop (Raes et al., 2018) were used and for the Delft-Agri model the RiBaSIM manual by Deltares was mainly used (Van der Krogt, 2008). Moreover, personal communication with the developers of both models has been used as information source in order to make model comparisons.

All information on both models led to a description of the model differences in input variables, processes and definitions. The focus of definitions is mainly on water use, as this is relevant for this study. The model descriptions lead to concrete differences which are presented in an overview in the results chapter.

3.2 Model performance in an average year

To answer research question 2 on the performance of both models during average years, the methods for validation of the output of both models to test their performance are described.

3.2.1 Validating output of Aqua21

In order to test the performance of the Aqua21 model, validation data has been used to validate the output of the Aqua21 model. Validation has been done on three output variables: production (tonne), wet yield, which is the mass of crops including incorporated water per hectare (tonne/ha), and harvested area (ha). For all three variables the output is given per crop (irrigated and rainfed crops together), per year for the period 1980-2010 in Aqua21.

The used validation data, production (tonne), wet yield (tonne/ha) and harvested area (ha), is on a regional level (NUTS-1) (Eurostat, 2020). This type of data is not readily available; a number of countries within the Rhine basin do or did not collect wet yields at this level or do not publish it. Thereby, France, Switzerland, Austria, Luxembourg, Belgium and the Netherlands cover per country just a small part of the Rhine basin (Figure 30 and Figure 31, Appendix E). Germany, on the other hand, covers a large part of the Rhine basin (Figure 30, Appendix E) and therefore production, wet yields and harvested area data for their federal states (Bundesländer) is asked for as validation data. The Rhine basin crosses eight federal states (Figure 4), however three of them (Lower Saxony, Thuringia and Bavaria) have relatively small land coverage in the basin. Therefore, the validation data is limited to five of the states: North Rhine-Westphalia, Rhineland Palatinate, Hesse, Saarland and Baden-Württemberg.

The required data for validation assessment was gathered from Destatis (The Federal Statistical Office of Germany) and includes production, wet yield and harvested area data for irrigated and rainfed crops together, for the single years of the period 1980-2010 for the four crops considered in this research (potatoes, sugar beet, maize and oats). Since data prior to 1989 is not available, not each Bundesland has data available for each year and because the processing of data is a time-consuming undertaking since data has to be transferred from scanned files into excel files manually, two crops will be used for validation. The selected crops are maize and sugar beet, this is based on four criteria; the first criterion considers the presence of data of dry years in the model output (both in Aqua21 as Delft-Agri) in order to make comparisons specifically for dry years (which is necessary for research question 3). The second criterion considers the fluctuation in production over the years of the model output. If the fluctuation is also seen in the validation data then high correlation can be expected. The third criterion looks at outliers and missing data in the model output. Crops with missing data in the model output are valued lower than crops without missing data. The fourth criterion considers the correctness of the validation data in terms of reporting; data should be reported and defined in the same way as data of the models, otherwise data is not comparable.

In terms of crop definitions used as terminology in the models, the FAO (2020b) is used as a guideline. The definition of sugar beet excludes fodder beet. The category potatoes excludes sweet potatoes and potatoes for fodder, as these are registered under different numbers. For cereal crops such as maize and oats, the data relates to crops harvested for dry grain only. Cereal crops harvested for hay or harvested green for food, feed or silage or used for grazing are excluded (FAO, 2020b).

Since the model output of Aqua21 can be given for any geographical composition, production (tonne), wet yields (tonne/ha) and harvested area (ha) are given per crop (irrigated and rainfed crops together), per year for the period 1980-2010 on Bundesland level. This has been done for the five selected Bundesländer (Figure 4). The output and validation data are checked for outliers according to the 1.5*IKA (interkwartielafstand) rule (Moore and McCabe, 2008). This rule implies that data which lies outside 1.5 times the interquartile range, is defined as an outlier. In this study, if outliers are present, they are investigated more precisely, because they may indicate model errors.

After all output data and validation data is collected, actual validation takes place. This is done with the help of the statistical method correlation. Correlation measures the direction and strength of the linear relationship between two quantitative variables (Moore and McCabe, 2008). This is done with the following equation:

$$r = \frac{\Sigma(x - x_{average})(y - y_{average})}{\sqrt{\Sigma(x - x_{average})^2 \Sigma(y - y_{average})^2}} \quad (1)$$

In which r stands for correlation, x for the single values in matrix 1, $x_{average}$ for the average value of matrix 1, y for the single values in matrix 2, $y_{average}$ for the average value of matrix 2. The closer r is to +1 or -1, the stronger the relationship.

The correlation is determined for the overlapping years of the model output data and the validation data of the period 1980-2010.

Figure 4: Federal states of Germany which are crossed by the Rhine basin (the dark blue ones are used in this research) (Erkalaycioglu, 2019)

3.2.2 Validating output of Delft-Agri

In order to test the performance of the Delft-Agri model, three output variables of the Delft-Agri model are validated: production (tonne), irrigation water supply to the system (m^3) and river discharge (m^3/s).

The first variable to be validated, production (tonne), results from Delft-Agri per crop, per sub-basin, per year for the period 1980-2010. The productions result from the crop plan irrigated crops (Table 2). It is validated against the crop plan of irrigated crops and its resultant production per crop per sub-basin, as derived from Aqua21 (Hogeboom et al., 2020). This is done for both sugarbeet and maize for each year in the period 1980-2010 for five sub-basins: Mosel/Saar, Main, Neckar, Hochrhein, Bodensee/Alpenrhein. These five sub-basins are chosen for validation because they have large land coverage for the crops sugarbeet and maize. Besides, they are located at the edges of the Rhine basin and are therefore less influenced by other sub-basins from a hydrological perspective, for example by infiltrating groundwater flows.

The second variable to be validated, net irrigation water supply to the system (m^3), results from Delft-Agri and includes the yearly supply (if rainwater, stored in the soil, is insufficient) from surface water to the system during the growing season in order to reach maximum potential productions. The net irrigation water supply (m^3) is equal to the net irrigation water requirement (m^3) if sufficient surface water is available for irrigation. The equation for the net irrigation water requirement of a sub-basin is:

$$Dnet = \{(Psat + Fc * Evp + P) - Re\} * OvaIEf * surface * 10 \quad (2)$$

$$Re = Rdep * \frac{Reff}{100} \quad (3)$$

$$OvAIEf = Ecv * Enr * Efa / 10000 \quad (4)$$

With D_{net} the net irrigation water requirement of a sub-basin (m^3), P_{sat} the pre-saturation requirement (mm/day), F_c the crop factor (this is equal to K_c), Evp the reference crop evapotranspiration (mm/day), P the percolation (mm/day), Re the effective rainfall (mm/day), R_{dep} the dependable rainfall (mm/day), R_{eff} the rainfall effectiveness (depending on the water supply to the area and the actual moisture on the field), surface the harvested area of the crop (ha), OvAIEf the overall irrigation efficiency (%), E_{cv} the surface water conveyance efficiency which is the efficiency of the main canals in the system (%), E_{nr} the normal period irrigation efficiency (%) which is the efficiency in the smaller canals managed by the farmers, E_{fa} the field application efficiency (%) which is the efficiency that depends on the type of irrigation. The efficiencies have to be multiplied in order to know the efficiency over the whole distribution system (E-mail correspondence with Van der Krogt, January 2, 2021). In Delft-Agri the efficiencies are set at 80% (in dry conditions this can go up to 90%), this means that 80% of the water will become effectively available to the plants and 20% will be lost to evaporation and seepage and to inefficient operation in the distribution system. A factor 10 is added to convert mm (water depth) into water volumes per area (m^3/ha).

The net irrigation water supply to the system (m^3) is validated against the Blue Water Footprint (BWF) (m^3) as derived from Aqua21 (Hogeboom et al., 2020). The BWF is calculated by accumulation of daily evapotranspiration of irrigation water and capillary rise (ET, mm/day) over the complete growing period of the crop, and so the BWF represents the total irrigation water evaporated from the field. The equation is as follows:

$$BWF = surface * 10 * \sum_{d=1}^{lgp} ETblue \quad (5)$$

In which a factor 10 is added to convert mm (water depth) into water volumes per area (m^3/ha). Lgp stands for Length of Growing Period in days. For crops and trees, which are permanently there and produce multiple yields, the annual average of ET over the full lifespan of the crop or tree should be considered in the calculations (Hoekstra et al., 2011). Surface stands for the harvested area of the crop (ha).

Another validation variable to estimate the performance of Delft-Agri is the river discharge (m^3/s), which is a variable related to the model package RiBaSIM. The validation data that has been used originates from the HYMOG project (Hydrological Modelling Basis in the Rhine Basin) (Steinrücke et al., 2012). In this project a high-resolution data basis is produced for the Rhine basin to perform hydrological investigations (Steinrücke et al., 2012). Discharge time series are generated per hour for the period 1990-2007 for several gauges. Appendix F shows the gauges considered in the HYMOG study (Steinrücke et al., 2012). For the validation in this study the gauges Cochem, Raunheim, Mainz and Basel are chosen (Appendix F shows their locations), because they are located in the sub-basins which are used for this study and which lie at the edges of the Rhine basin. Cochem and Raunheim are located in the side rivers respectively the Mosel and Main, Mainz and Basel in the main river: the Rhine. Data of some gauges such as Lobith in the Netherlands need further improvement in the HYMOG project, therefore these gauges are not chosen in this study (Steinrücke et al., 2012).

The river discharge (m^3/s) is extracted from the RiBaSIM model for the stations Cochem, Raunheim, Mainz and Basel per time step, which is the 10-day period. This data is extracted from the simulation in which the irrigated crops are implemented (Table 2). In the RiBaSIM Rhine model also other sectors such as the industry and the private sector are implemented as water users. Three methods were used to test the performance of the RiBaSIM model. For all three methods, this was done for the time period 1990-2007 with a 10-day time step. First the method of correlation, as described in 3.2.1 equation (1), was used to estimate the correlation between the modelled river discharge of RiBaSIM and the validation data of HYMOG. Also, the Nash-Sutcliffe Efficiency (NSE) method was used. The NSE measure goes to 1 as the fit between the simulated output and the validation data improves. A value between 0.6 and 0.8 indicates that the model performs reasonably. Values between 0.8 and 0.9 indicate that the model performs really well and values between 0.9 and 1.0 indicate that the model performs extremely well (Nash and Sutcliffe, 1970). The equation reads:

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(Qobs - Qsim)^2}{\sum_{i=1}^{N}(Qobs - Qobs,mean)^2} \quad (6)$$

With Q_{obs} the observed discharge (HYMOG validation data) (m^3/s), Q_{sim} the simulated discharge by the RiBaSIM model (m^3/s), $Q_{obs,mean}$ the mean observed discharge (m^3/s) and N the total number of time steps.

The third method used, was the Relative Volume Error (RVE) to quantify the volume error between the simulated discharge (m^3/s) and the validation discharge (m^3/s). The RVE can vary between -∞ and ∞ but performs best when a value of 0 is generated, because that indicates no difference between both datasets (Janssen and Heuberger, 1995). A relative volume error less than + 5% or -5% indicates that the model performs well, whereas relative volume errors between +5% and +10% and -5% and -10% indicate a model with reasonable performance (Gumindoga, 2010). The RVE equation reads:

$$RVE = \left[\frac{\sum(Qsim - Qobs)}{\sum(Qobs)}\right] * 100\% \quad (7)$$

3.3 Model performance in a dry year

The third research question considers the model performance during dry years. A prerequisite to estimate the performance, is to identify the dry years. Therefore, first the dry years are identified (section 3.3.1), followed by the methodology on estimating the performance of both Aqua21 (3.3.2) and Delft-Agri (3.3.3) during these dry years.

3.3.1 Identifying dry years

A dry year is determined on the degree of dryness in the drought season. The drought season is from the first of April till the first of October (KNMI, 2020c; Rijkswaterstaat, 2020b). Drought indicators like rainfall deficit, discharge, soil moisture, groundwater level are till now calculated with data of this summer period (KNMI, 2020b). Normally, during the winter period water levels in the soil went back to 'normal' and the drought of a new summer season could be calculated from April onwards. However, over the last years it has been noticed that these water levels were not replenished during winter (cumulative drought) and therefore new definitions and ways to calculate drought are in development (KNMI, 2020b). These developments are also seen in policy; when dry periods occur (for example in 2018 in the Netherlands) policies such as the 'verdringingsreeks' (priority ranking for water supply under conditions of water shortage) have to be applied since a long time, and it turned out that there was a need by water managers to get additional explanation and clarification on certain definitions. Therefore an additional manual has been published (Kort and Teunis, 2020). These examples show that in the Rhine basin the phenomenon drought currently is in development in terms of definitions and ways to calculate it.

In this study, drought has been estimated with the drought indicators rainfall and discharge deficit. The indicator rainfall was used as a cumulative indicator, which means that the rainfall of the whole calendar year was included and not just the summer period. For every year in the period 1980-2010 the average rainfall over the whole year was calculated in mm (Hogeboom et al., 2020) (Figure 5). The 20% driest years in this period are: 1989, 1990, 1991, 1996, 2003, 2004.

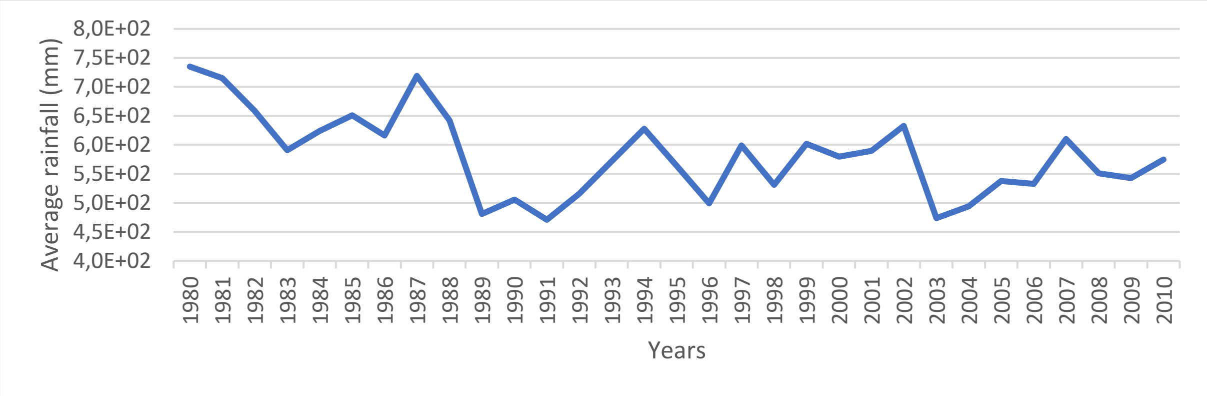

Figure 5: Average rainfall (in mm) per year for the period 1980-2010 in the Rhine basin (Hogeboom et al., 2020)

The second indicator for drought, discharge deficit, has been calculated with discharge values at Lobith (Rijkswaterstaat, 2020a). For this indicator only the summer season (April 1 – October 1) is taken into account as discharge is no cumulative factor. The discharge deficit was determined with respect to a discharge threshold of 1.800 m^3/s (this threshold has been used in earlier studies by Deltares considering the Rhine basin (Ter Maat and Vat, 2015)). The deficit (m^3) was summed by taking all daily discharges that are lower than 1.800 m^3/s in the summer half year. This means that a Rhine discharge of for example 1.000 m^3/s corresponds to a discharge deficit of 800 m^3/s, while for a discharge of 2.000 m^3/s a discharge deficit of 0 m^3/s is calculated. The results of the discharge deficit per summer half year for the period 1980-2010 are depicted in Figure 6. For this indicator also the top 20% was taken, the years with the highest deficit are: 1990, 1991, 1993, 1996, 1998 and 2003.

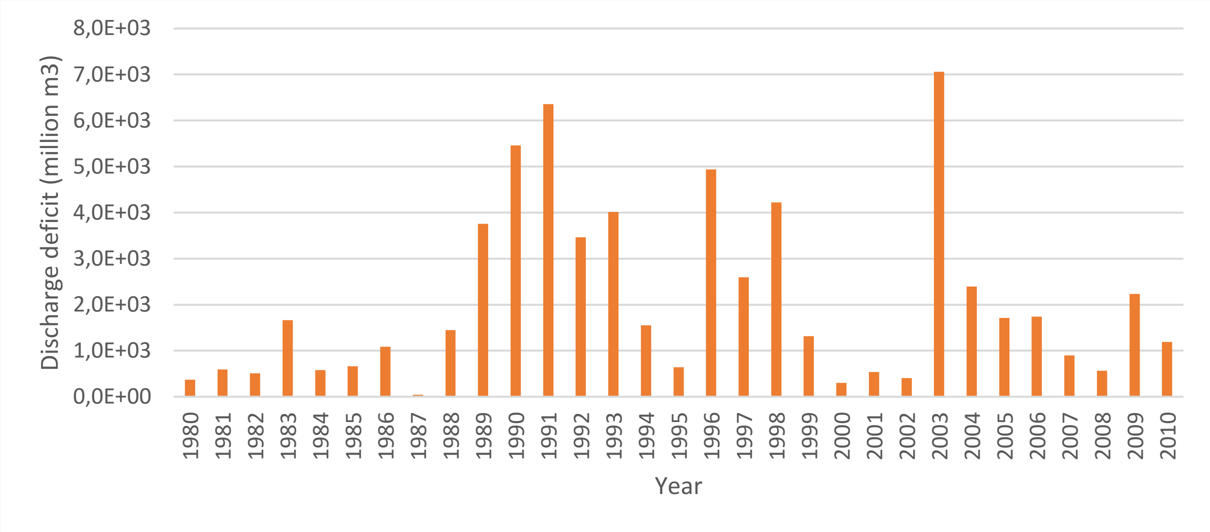

Figure 6: Discharge deficit (with a threshold of 1.800 m3/s) for the summer half year for the period 1980-2010 at Lobith (Rijkswaterstaat, 2020a)

Both indicators, rainfall and discharge deficit, have equal weight in determining the dry years. The corresponding dry years for both indicators are 1990, 1991, 1996 and 2003. Therefore, these four years were selected as dry years in the period 1980-2010.

3.3.2 Validating output of Aqua21

To estimate the performance of the Aqua21 model during dry years, dry years have been selected in the model output and validation data (out of the time series generated for the period 1980-2010). This means the same procedure is followed as for the average years (section 3.2.1), but now for the subset of dry years (as defined in 3.3.1). Again, validation has been done on three output variables: production (tonne), wet yield (tonne/ha) and harvested area (ha). However, whereas correlation has been used for the average years, descriptive statistics are used to analyse the dry years.

3.3.3 Validating output of Delft-Agri

To estimate the performance of the Delft-Agri model during dry years, dry years have been selected in the model output and validation data (out of the time series generated for the period 1980-2010). This means the same procedure is followed as for the average years (section 3.2.2), but now for the subset of dry years (as defined in 3.3.1). Again, validation has been done on the following variables: production (tonne), irrigation water supply to the system (m^3) and river discharge (m^3/s). However, whereas for the average years, the correlation, NSE and RVE between the modelled river discharge (m^3/s) of RiBaSIM and the validation data of HYMOG have been estimated for all years, for the dry years the correlation, NSE and RVE have been estimated for only the dry years. By doing so, it can be determined if the model deviates more or less from the validation dataset when only periods of drought are considered.

The methodological approach of the research so far (sections 3.1, 3.2, 3.3) is summarized in Figure 7: the conceptual model. The focus is on the used models Aqua21 and Delft-Agri and their relation to the validation.

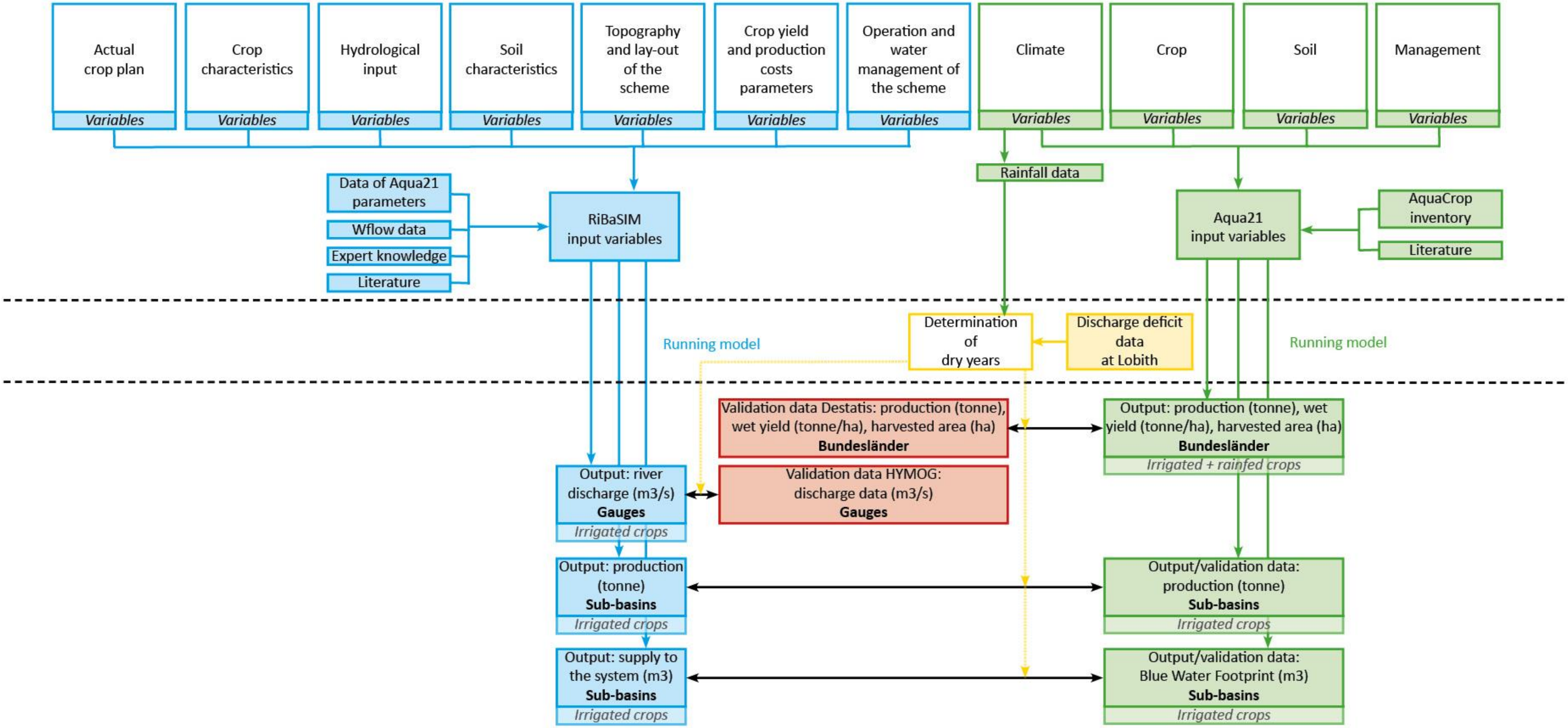

Figure 7: Conceptual model of the methodological approach of the research. The focus is on the used models RiBaSIM (blue) and Aqua21 (green) and their relation to the validation. Determination of dry years is depicted in yellow, the validation data of Destatis at Bundesländer level and HYMOG at gauge level are shown in red. The arrows show the connections between the datasets, blue and green arrows between the RiBaSIM and Aqua21 datasets respectively. Yellow arrows show the influence of dry years on the validation and black arrows show the connections between datasets on which the models are validated.

3.4 Scenarios

To answer the main question of the research on estimating the possible future irrigation water requirements in the Rhine basin during the growing season in periods of drought, scenarios are used. Scenarios are 'images of the future, or alternative futures' according to the Intergovernmental Panel on Climate Change (IPCC) in Nakicenovic et al. (2000). In this section, first the method for designing plausible agricultural scenarios in the context of increasing drought is explained (3.4.1). Then, an explanation on the model used to run the scenarios is given (3.4.2).

3.4.1 Designing scenarios

In international environmental assessments in which future environmental problems such as drought are evaluated, scenarios are used as a useful tool to resolve those problems (Alcamo, 2001). One of the methods used in the field of environmental assessments is the 'story-and-simulation'(SAS) approach, which is often used by the Intergovernmental Panel on Climate Change (IPCC) and World Water Commission (WWC). The approach can be described as follows: "a combination of qualitative and quantitative information, consisting of two elements: a storyline and a set of model calculations. The storyline describes how the events might unfold in the future, and the model calculations are complementary to the storyline by presenting numerical estimates" (Alcamo, 2001). Figure 8 shows the steps of the SAS approach. This research uses the SAS approach as a guideline. The steps of the method are explained, including a description on how the step has been carried out for this study.

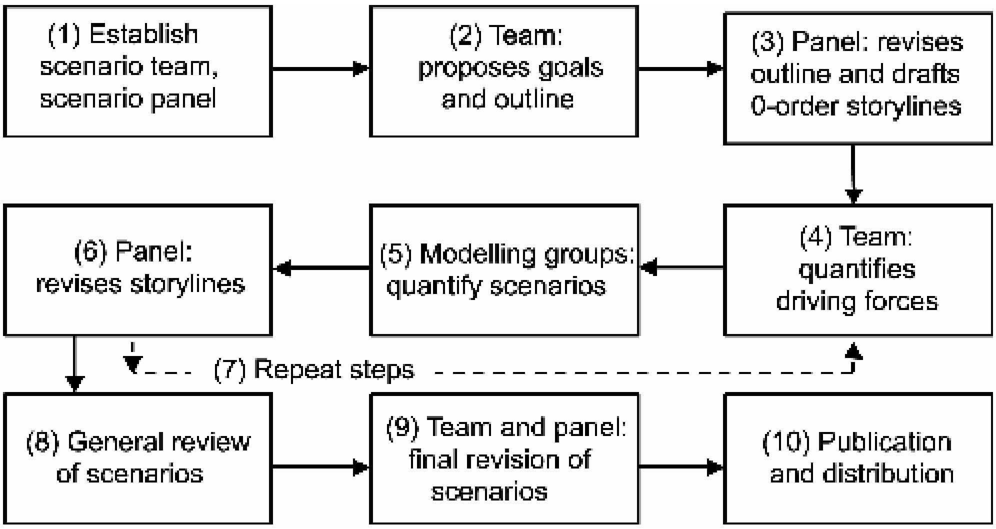

Figure 8: Steps in the Story-and-Simulation approach (van Vliet and Kok, 2007) *based on the work of* (Alcamo, 2001)

The first step consists of establishing a scenario team and panel. The scenario team coordinates the scenario building and consists of representatives from the institution. The scenario panel provides creative input and ensures that various perspectives of the problem are taken into account, it consists of policymakers and additional experts (Alcamo, 2001). In this study the scenario team consists of the author of the report and the supervisors of the report. The scenario panel is represented by two scenario building experts from the department of Economy, Scenarios and Innovation of Deltares.

In the second step, a first outline of the scenarios is proposed by the team. In this study the author of the report made an outline of the goals of the scenarios, the subjects that the scenarios had to cover and the time horizon of the scenarios.

In the third step, the panel is involved. In this step the panel discusses and revises the goals of the scenarios and drafts a zero order storyline of the scenarios. A zero order storyline is a first draft, which consists of preliminary sketches of the main events in the scenarios (Alcamo, 2001). In this study the main themes of the scenarios, the number of scenarios and the time horizon were determined by the panel and author of the report.

In step four, numerical values are assigned to the driving forces of the scenarios based on the draft storyline. The scenario team quantifies the driving forces, mostly based on data from previous studies (Alcamo, 2001). In this study, the author, in consultation with the supervisors of the report, assigned values to the driving forces based on previous studies.

During the fifth step, the modelling team quantifies the scenarios. The team computes the indicators of the scenarios. In this study, the author of the report prepared datasets of each scenario.

In step six, the storylines are revised by the panel. The modelling team presents the quantification of the draft storylines and the panel points out where there are possible inconsistencies (Alcamo, 2001). In this study, the author of the report asked the panel to provide feedback on the quantification of the draft storylines. The panel provided feedback and after discussion of the feedback, the draft storylines were revised by the author.

In step seven, an iteration of step four, five and six might take place due to possible discussions in step six. The steps must be repeated until the scenario team and panel agree on the storylines and their quantification (Alcamo, 2001). In this study, step 7 has not been carried out since there was agreement on the storylines and their quantification.

Step eight and nine include the general review of scenarios by experts and stakeholders and the revision of the scenarios. A general review can be accomplished by publicising scenarios on various platforms. The revision of the scenarios is done by the team and the panel. In this study, these two steps were not taken into account because of time limitations in conducting the study.

Step ten is the publication and distribution of the final scenarios. In this study, this is done in chapter 4.

3.4.2 Simulating scenarios

After designing the scenarios, they were simulated. Input data in the water demand and allocation model Delft-Agri was adjusted (which means that scenarios were implemented). Since this model computes both irrigation water requirements and river flow, Delft-Agri is used to simulate the developed scenarios. To calculate the change in evapotranspiration, the Blaney-Criddle method (Brouwer and Heibloem, 1986), which is a method based on temperature only, is used. The Blaney-Criddle equation reads:

$$\Delta ET = p\ (0{,}46 * \Delta Tmean + \ 8) \tag{8}$$

With p the mean daily percentage of annual daytime hours and ΔT the change in mean daily temperature (Celsius). Values for p were determined based on latitude (Brouwer and Heibloem, 1986).

In order to estimate the current and possible future irrigation water requirements and the impact on river flow, the crop plan for only irrigated crops was used (Table 2). A reference scenario was simulated and represented the current state of the irrigation water requirement and its impact on river flow. The designed scenarios by the scenario team and panel were also simulated and represented the possible future state of the irrigation water requirement and its impact on river flow.

4. Results

4.1 Model comparison

In chapter 2 a brief overview is given of both agricultural models: Aqua21 and Delft-Agri. In this section more detailed information is given on the model inputs, processes and definitions of water use and comparisons are made.

4.1.1 Input variables

The Aqua21 input variables are listed in Table 13, Appendix G. Aqua21 and Delft-Agri have many equal variables, however some of the variables are included in just one of the models.

This happens to the parameter 'planting period', it is included in Delft-Agri and covers the amount of time steps to plant the crop. This has been included in the model because at the beginning of the growing period a peak in water is demanded from the system. In Aqua21, this planting period is not taken into account, because the model looks into the water requirement of a single plant and not into the water requirement of the whole water system.

Another difference is the use of the variables 'CO_2 concentration' and 'minimum and maximum air temperature'. These variables are used in Aqua21 because they influence the atmosphere and so the biomass productivity (Raes et al., 2018). Delft-Agri does not use these variables. Temperature influences the growing degree days (GDD) of a plant and GDD is used to calculate the Canopy Cover (CC) in the phenological model Aqua21. Delft-Agri, on the other hand, includes temperature only in the ET_0 variables by having different ET_0 values over the basin.

4.1.2 Processes

Aqua21 and Delft-Agri have different modelling processes, especially for calculating crop evapotranspiration (ET_c), for handling fluxes in the soil, and for calculating yield formations. These three processes are explained in detail for both models in Appendix H.

The difference in the calculation of crop evapotranspiration (ET_c) between the two models is that Aqua21 uses various stress coefficients which have an influence on the ET_c at a certain stage of the plant growth, whereas in Delft-Agri stress coefficients are not taken into account. Also, the transpiration coefficient is proportional to the canopy cover in Aqua21 and so includes ageing and senescence effects, whereas in Delft-Agri the transpiration coefficient is proportional to the crop coefficient K_c, which is linearly interpolated between the plant growth stages.

Concerning the processes in the soil, Aqua21 and Delft-Agri both consider fluxes that go in and out of the soil as explained in Appendix H.2. Aqua21 does consider the hydraulics of water movement in the root zone, whereas Delft-Agri does not. Therefore, Aqua21 describes surface run-off, water and salt movement, water infiltration and retention much more accurately than Delft-Agri. Furthermore, Aqua21 separates soil evaporation from crop transpiration. The hydraulics in the root zone are taken into account by dividing the soil into 12 compartments (Δz) which cover the entire root zone, and by putting the time step (Δt) is into small fractions. In each simulation run, values per compartment and time step are calculated (Raes et al., 2018). Soil water movement happens by drainage, capillary rise and surface run-off. They all have a common factor in their calculations: the use of the saturated hydraulic conductivity (K_{sat}). This means that in Aqua21 the type of soil is needed as an input variable, as each type of soil has a different K_{sat}. This makes it different from Delft-Agri, wherein the type of soil is not taken into account. Therefore the calculations of drainage and surface run-off are different as well.

In Delft-Agri drainage is computed as a rest term, which means that if the storage in the field is above the desired level and above the field buffer storage then the extra water is considered as drainage (Van der Krogt, 2008). In Aqua21, however, a drainage function is used to determine the amount of drainage. The function describes the decline in soil water content between saturation and field capacity with a tau factor. The tau factor is proportional to K_{sat} and further explained in Appendix H.2.

Capillary rise is not considered in Delft-Agri, but in Aqua21 it is considered by using the soil classes and their K_{sat} values. To compute the amount of water that moves upward, the soil water content at the bottom of the root zone is considered, as this determines the driving force. A so called CR-Z curve (capillary rise CR – depth of root zone Z) determines the potential capillary rise, from which the actual CR is deduced (Raes, 2017).

Surface runoff also is a process that is differently handled by the two models. In RiBaSIM, which is a water demand and allocation model based on a network of nodes and links, the runoff from one area is used as input for another area. Whereas in Aqua21, surface runoff is just seen as an output factor in the water balance. Besides, Aqua21 does not simulate surface runoff when water is applied by irrigation, because it assumes full control of water by the farmer (Raes, 2017). By simulating in this way, the specified irrigation amount can be handled as net irrigation water. RiBaSIM deals with gross water demand, since water from both rainfed as irrigated areas can become runoff (Van der Krogt, 2008). Runoff from the rainfed areas is computed by Wflow, runoff from the irrigated areas results from inefficiencies in the irrigation system and from the water balance of the field(s) as computed by Delft-Agri.

To account for water stress in the soil, the Aqua21 model uses the K_s variable. The same as for Delft-Agri, the soil moisture should lie between the permanent wilting point and the field capacity. Whereas in Delft-Agri this process is not described in much detail (if the moisture is below wilting point, the crop will have damage, however the margin between little damage and total loss is relatively small), Aqua21 describes the process between the two levels with the detailed K_s curve (depicted in Appendix H.2). The shape of the K_s curve determines the magnitude of the effect of water stress in the soil. For each process, the K_s coefficient has its own values and thresholds (Raes et al., 2018).

The processes for calculating yield also differ between the two models. The equations for both models are explained in Appendix H.3. The main difference between the calculation process is that Aqua21 takes into account the canopy cover development including stresses that might occur during the growing process, whereas Delft-Agri makes use of a linear relationship between actual evapotranspiration ET_a and yield formation. Delft-Agri accounts for stress if the soil moisture drops below wilting point. However, the margin between little damage and total loss is relatively small, resulting in giving up a crop in case the field moisture falls below the root zone soil moisture for drought stress, in the present modelling scheme (Van der Krogt, 2008).

4.1.3 Definitions of water use

The definitions of water use for both models is given in Appendix I. The main difference between the two models is that in Aqua21 water use refers to water consumption, whereas Delft-Agri refers to water use as water withdrawal (both net and gross withdrawal). Both models are able to differentiate between blue and green water use.

4.1.4 Overview

In this section an overview of the model comparisons is given. Table 5 shows how Aqua21 and Delft-Agri handle several aspects of modelling water use. The comparisons have been divided into input data, processes, output data and other.

Table 5: Overview of model comparisons between Delft-Agri and Aqua21

	Delft-Agri	**Aqua21**
Input data		
Planting period	Yes, the amount of time steps to plant the crops is included	No, but planting and sowing dates are included
Hydrological	Yes, see Table 4	Yes, see Table 13
Crop characteristics	Yes, see Table 4	Yes, see Table 13

Topography	Yes, as a background map in the RiBaSIM model package for the Rhine basin	No, but database can be linked to mapping programs like QGIS
Soil texture	No	Yes
Soil types	No (but indirect via wilting point, field capacity and saturation capacity parameters)	Yes, soil classes are included
Irrigation method	Yes, rotational irrigation can be simulated. Also irrigation application efficiencies can be set.	Yes, various irrigation methods can be used: sprinkler, drip or surface.
Growing process	Yes, with calender days	Yes with Growing Degree Days
Air temperature	No (incorporated in ET_0)	Yes
CO_2 concentration	No	Yes, one value per year for all cells
Reference ET	Yes	Yes
Processes		
ET_c	With the use of K_c values	With the use of CC value and stress coefficients
Water balance in the soil	Includes: rainfall, irrigation water supply, evaporation, drainage, seepage/percolation Excludes: capillary rise	Includes: rainfall, irrigation water supply, evaporation, drainage, seepage/percolation, capillary rise
Water stress in the soil	Water stress is not described: when soil moisture is below wilting point, the crop is damaged. However, the margin between little damage and total loss is relatively small.	Soil moisture should be between two levels. Water stress is described in more detail with the help of the Ks curve
Hydraulics in the root zone	Not considered	Considered: by dividing the soil in compartments
Output data		
Gross water requirement	Yes	No (run-off of irrigation water not included)
Net water requirement	Yes	Yes
Crop yield	With K_y (yield response factor)	With HI and B (harvest index and biomass)
Supplied irrigation water	Yes	Yes, this is equal to the Blue Water Footprint

Conveyance losses	Yes (by field water balance and efficiencies)	No, since Aqua21 is not an water allocation model
Water balances at various levels	Yes, per cultivation, per irrigation area/ field and for the whole basin	Yes, per grid cell, which can be aggregated to any other level
Other		
Routing	Yes	No
Time step	Daily, weekly; 10 days; half- monthly; monthly	Daily
Use of field data	Hardly	Yes, such as depth and salinity groundwater table, use of mulches etc. See appendix C.3.

4.2 Model performance in an average year

In this section, the second research question on the performance of the models during average years is answered. The section starts with the selection of crops for the performance assessment (4.2.1) and then the results of respectively Aqua21 and Delft-Agri are presented and tested (4.2.2, 4.2.3).

4.2.1 Crops for performance assessment

The crops for the performance assessment are selected based on four criteria. 'Maize' and 'sugar beet' scored best on the criteria and are therefore selected. The first criterion considered the presence of data for dry years in the model output of both models. Both maize and sugar beet have output for dry years, and therefore this criterion is met. The second criterion, which considered the fluctuation in production over the years in the model output is also met, since there is fluctuation in production between the years in the model output (this is based on Aqua21 model output)(Appendix J). On the third criterion concerning outliers and missing data, maize and sugar beet both showed an outlier at 1996, this resulted from the Aqua21 output on production, yields and harvested area. Besides, for maize there was some missing data. However, 'potatoes' also had outliers and missing data, oats on the other hand performed good on this criterion with having no outliers and no missing data, however oats performed lower on the other criteria and has therefore not been selected. The fourth criterion considered the correctness of the validation data in terms of reporting, in order to compare it to the model output of Aqua21 and Delft-Agri. Maize validation data has been reported as Kornermais including CCM (Corn Cob Mix), silage maize has been reported separately (Destatis, 2020b). In this study, Kornermais (including CCM) is used as this is comparable to the output data of the models (see chapter 3.2.2 for FAO maize definition). Sugar beet validation data has been reported as Zuckerrüben, Runkelrüben are reported separately (Destatis, 2020b). In this study, Zuckerrüben are taken for comparison, as Runkelrüben are used as fodder crops.

4.4.2 Performance of Aqua21

Three output variables were used to estimate the performance of the Aqua21 model: production (tonne), wet yield (tonne/ha) and harvested area (ha). For all three variables the output is given for the selected crops maize and sugar beet (irrigated and rainfed crops together), per year for the period 1980-2010 per Bundesland. The Aqua21 model output is plotted against the same variables from the validation data (Destatis, 2020b). The results for the production for all selected Bundesländer can be seen in Appendix K. Figure 9 shows the production results for sugar beet for Baden-Württemberg. Outliers are marked with a red shell and are investigated more precisely, because they may indicate model errors. The variable production is plotted, because it includes both the variable yield (tonne/ha) and the variable harvested area (ha), because these are multiplied to get total production. In the analysis of the production variable, also the variables yield and harvested area were further analysed per Bundesland.

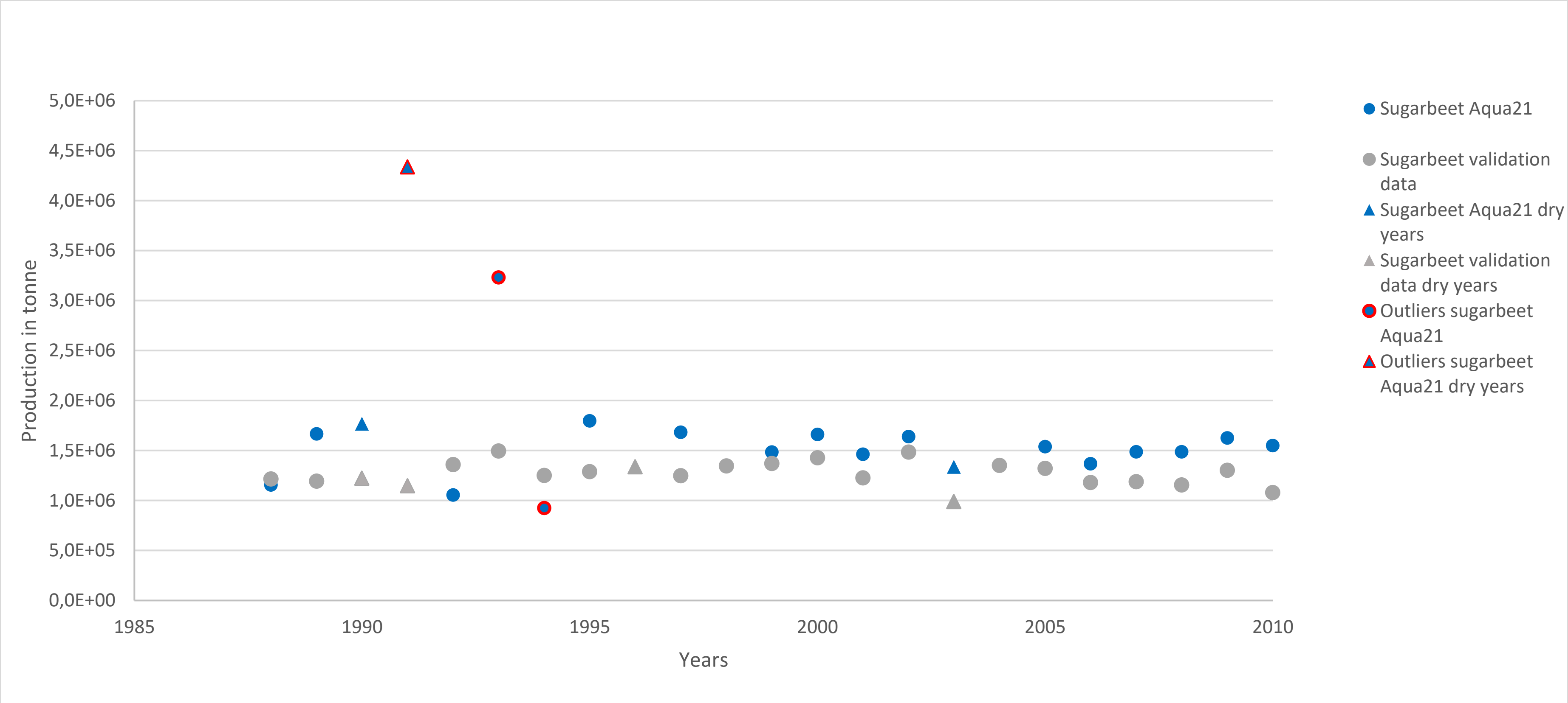

Figure 9: Validation on yearly production model output of sugar beet (Aqua21) in tonnes for Baden-Württemberg

A first analysis of the results showed that there were some peaks (and for some Bundesländer outliers) in production data (Figure 9). The peaks (and outliers) were only seen in the Aqua21 data, but not in the validation data. Also, they were mostly noticed for sugar beet and not for maize (Appendix K). Most of these peaks occured in the period 1991-1993; the period in which Germany united. As the yield and harvested area data of Aqua21 were scaled to national statistics, these peaks could relate to a change in registration of data. In Appendix L both variables were further investigated and the production (tonne) variable turned out not to be influenced by scaling to national statistics since peaks for sugar beet and maize were seen both in the scaled as unscaled production data of Aqua21. The variable harvested area (ha), on the other hand, was influenced by scaling to national statistics since a small increase in harvested area for Germany was noticed for both sugar beet and maize around the year 1991 (Hogeboom et al., 2020). That means that the harvested area (ha) dataset is not homogenous for the period 1980-2010. For the validation datasets, the peaks were not seen in the harvested area nor yield data (Destatis, 2020a). So, the peaks in production (tonne) are mainly caused by the harvested area dataset of Aqua21.

Aqua21 production output (tonne) was mostly higher than the validation data (Figure 9). For sugar beet this was the case for all Bundesländer (except Saarland, because no data available for sugar beet), for maize this was the case for three out of five Bundesländer. This can be clarified by overestimation of harvested area (ha) by the Aqua21 model, because the yields of Aqua21 and the validation data match well.

In the Aqua21 model output there was some missing data for both crops in the period 1980-2010 for all Bundesländer. For all variables (yield, harvested area and production) data was missing for the years 1984 and 1996. In the validation data these years were not missing.

Both in the Aqua21 model output data, as well as in the validation data an increase in production (tonne) over the years was noticed, especially for maize. This can be clarified by the increase in yield (tonne/ha). For sugar beet also an increase in yield (tonne/ha) was noticed in both the Aqua21 model output as well as in the validation data. However, the harvested area (ha) of sugar beet slightly decreased over the years (both in model output as well as in validation data) and therefore the production (tonne) hardly changed over the years (Figure 9).

Besides the descriptive analysis, also correlation was estimated between the production (tonne) data of the Aqua21 model and the validation data. This has been presented in Table 6 for maize and sugar beet for the five selected Bundesländer. Overall, the correlation strongly varied both between the Bundesländer as well as between the two selected crops. In general, correlation was higher for maize than for sugar beet. For North-Rhine Westphalia high correlation for both crops was seen, which means the relation between the model output of Aqua21 and the validation data is determined as strong for this Bundesland (Clifford et al., 2010). For Rhineland Palatinate a moderate negative and positive correlation was seen between the Aqua21 model output and the validation dataset. Negative correlation means that the trend of data pairs is negative (trend line in Figure 10 whereas a positive correlation shows a positive trend of data pairs (trend line in Figure 11). For this study, the trend (positive or negative) had no influence on estimating the performance of the Aqua21 model. In the two scatterplots (Figure 10 and Figure 11) also the 1:1 line is shown; for sugar beet the production validation data and the Aqua21 output data are close to this line, which indicates good model performance (this is also seen for the other Bundesländer), whereas for maize the data pairs are not close to this line (this is also seen for the other Bundesländer). For Rhineland Palatinate, the Aqua21 production output for maize is almost four times larger than the validation data. So, although correlation is high, there might be consistent over or under estimation in Aqua21 model output. For sugar beet overestimation is limited, but for maize overestimation is noticed in four out of five Bundesländer with a factor 2 on average.

In conclusion, the performance of the Aqua21 model was estimated on the variables production (tonne), harvested area (ha) and yield (tonne/ha). The yield dataset of the Aqua21 model performed well, which means that the simulated yield is quite similar to the validation data. The harvested area dataset showed peaks and outliers, especially during the unification of Germany (1991-1993) due to scaling of this dataset to national statistics. Also, the harvested area dataset seemed to overestimate the harvested area of sugar beet and maize, which led to higher production (tonne) values in the Aqua21 model output compared to the production validation data. Therefore, the performance of the harvested area dataset of Aqua21 is limited. Furthermore, there was some missing data in the datasets of Aqua21. All in all, there is correlation between the Aqua21 production (tonne) model output and the validation data for all Bundesländer. However, for maize overestimations were seen in the Aqua21 model output with a factor 2 on average. The strength of the correlation varied per Bundesland, with North Rhine-Westphalia performing high.

Table 6: Correlation between annual production (tonne) in the period 1980-2010 as simulated by Aqua21 and validation data. N is the sample size.

	Baden-Württemberg	**Hesse**	**North Rhine-Westphalia**	**Rhineland Palatinate**	**Saarland**
Sugarbeet	0,07 (N=22)	0,19 (N=16)	0,32 (N=22)	-0,40 (N=20)	No data
Maize	0,50 (N=23)	0,11 (N=16)	0,73 (N=21)	0,37 (N=21)	-0,28 (N=11)

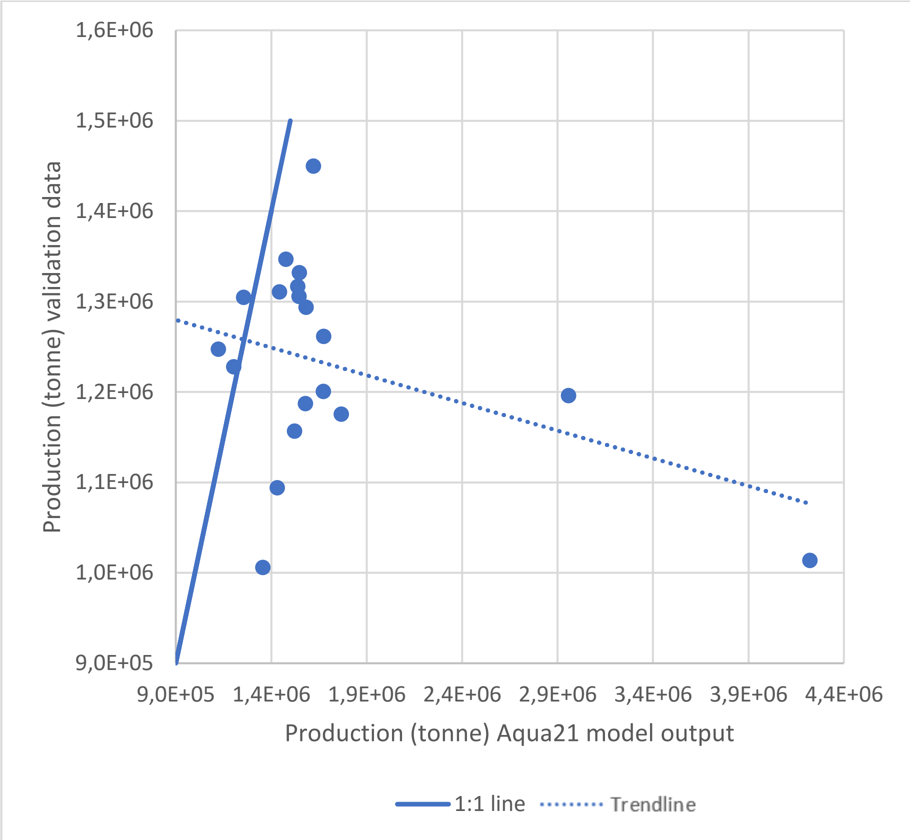

Figure 10: Scatterplot of yearly production output (tonne) of sugar beet for Rhineland Palatinate

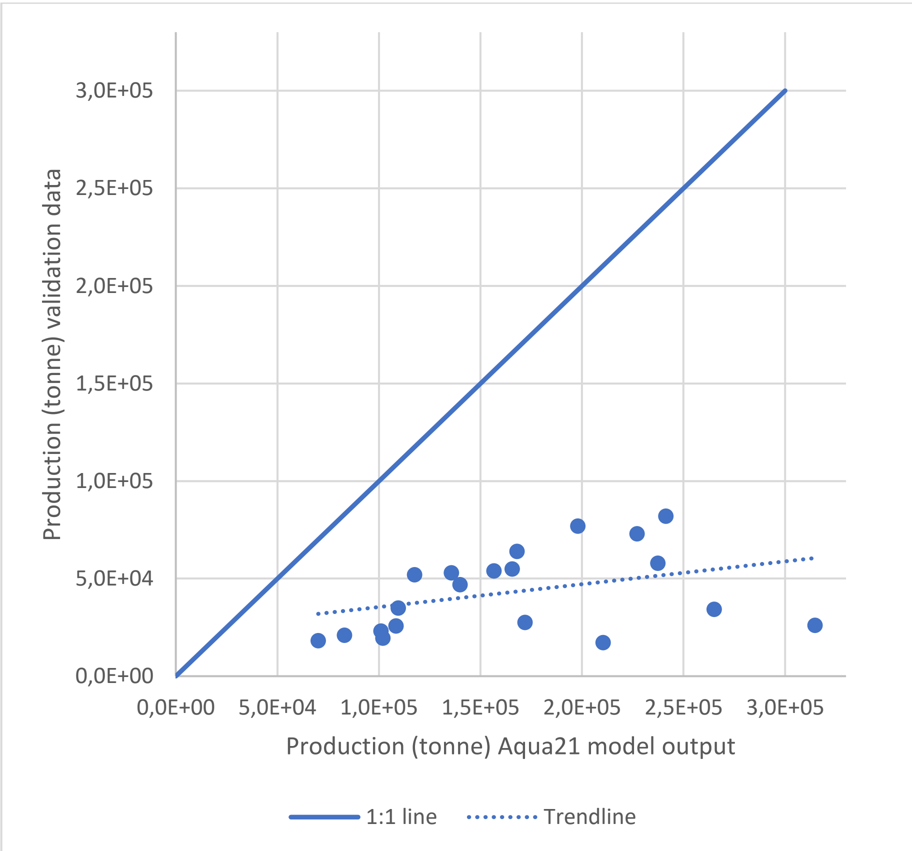

Figure 11: Scatterplot of yearly production output (tonne) of maize for Rhineland Palatinate

4.2.3 Performance of Delft-Agri

The performance of the Delft-Agri model has been tested with the output variables production (tonne), net irrigation water supply to the system (m^3) and river discharge (m^3/s).

First, productions of Delft-Agri for several sub-basins have been estimated and then a performance assessment was done against production according to Aqua21. Productions (tonne) for irrigated crops, both for sugar beet as well as for maize. Figure 12 shows the result for sugar beet for the Hochrhein sub-basin. The figure shows that, according to the Delft-Agri model, the potential production for sugar beet has been reached every year. It means that according to the Delft-Agri model there were no limitations in water supply from rainfall, soil moisture and irrigation water. The validation data in the figure, productions according to Aqua21, show two things: a trend over the years and inter-annual fluctuations. Since Aqua21 output was scaled to national statistics, a trend over the years can be explained by trends in management, for example crop breeding or use of minerals. In case of Delft-Agri trends were not expected since the yield and harvested area output was not scaled to national statistics. Inter-annual fluctuations in the Aqua21 production output can be related to drought damage, but also to a plague or to a storm with national impacts, since Aqua21 output was scaled to national statistics. In case of fluctuations in production output in Delft-Agri, drought damage can be the only cause.

In the production output (tonne) of Delft-Agri also potential productions have been reached for maize in the Hochrhein. Potential productions have also been reached for sugar beet and maize for all the other investigated sub-basins (Mosel/Saar, Neckar, Main, Bodensee) for all years. So, according to the Delft-Agri model, there were no restrictions in water supply.

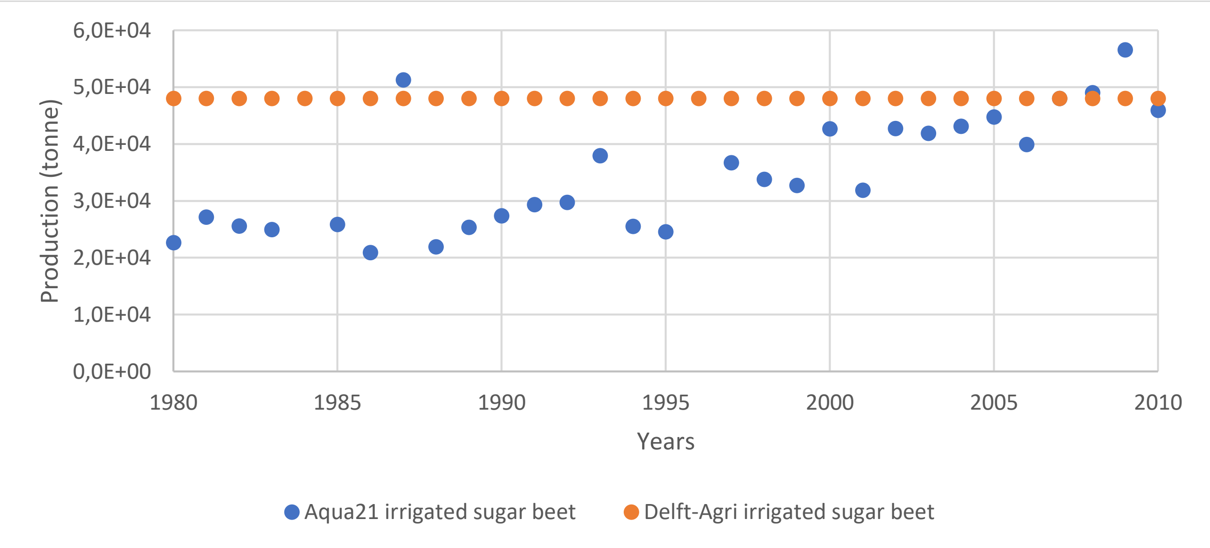

Figure 12: Yearly irrigated production Delft-Agri model output (tonne) for sugar beet in the Hochrhein.

The second validation variable, irrigation water supply to the system (m^3), is related to the production variable, because although potential productions were reached, the irrigation water supply changed over the years per sub-basin. In this case, because potentials productions were reached, the supply to the system (m^3) was equal to the net irrigation water requirement of the system (m^3). The net irrigation water supply to the system (m^3) was estimated for all four irrigated crops together during the growing season per sub-basin on a yearly basis. The results are depicted, together with the Blue Water Footprint (BWF) (m^3), in Figure 13 for the Hochrhein and for the other sub-basins in Appendix M. By testing the performance of the Delft-Agri model with the BWF variable it should be taken into consideration that in the BWF the ET of capillary rise is incorporated, whereas in the Delft-Agri model capillary rise is not considered. Therefore, Delft-Agri irrigation water supply to the system (m^3) output should be considered slightly higher. Correlations were estimated between the net irrigation water supply (m^3) and the BWF (m^3) per sub-basin (Table 7). Correlations were low, since the Delft-Agri model used one crop plan (based on the year 2000) (Table 2) for the whole simulation period and therefore no large inter-annual fluctuations are. Aqua21, on the other hand, made use of a different irrigated crop plan each year, therefore larger inter-annual fluctuations were noticed. For the year 2000, in which the crop plans of both models were equal, similarity in irrigation water supply (m^3) between the two models was seen for 3 out of 5 sub-basins (for the Hochrhein see Figure 13). Based on that, the performance of the Delft-Agri model is considered as good. However, for the other 2 sub-basins (Main and Mosel/Saar Figure 50 and Figure 51 respectively, Appendix M) the outputs of both models differed far from each other in both directions. For the Main, where net irrigation water supply (m^3) is much larger than the BWF (m^3), this is clarified by the unlimited access to irrigation water in the Delft-Agri model due to the distribution of the irrigation nodes. In Delft-Agri each sub-basin has one irrigation node in which surface water of the whole basin is accessible. However, in reality irrigation areas are distributed over the sub-basin leading to smaller upstream areas with limited access to surface water. The Aqua21 model encountered limiting access to water resulting in dying of plants during the growing season. Therefore, the BWF of Aqua21 was smaller compared to net irrigation water supply of Delft-Agri. The limited irrigation water supply to the Mosel/Saar in the Delft-Agri model might result from the limited harvested area of irrigated crops in this area (Table 2), however this was not reflected by the Aqua21 BWF output. All in all, the Delft-Agri model performed good on the variable net irrigation water supply (m^3) in case irrigation water is unlimited accessible. However, in case of limited access to irrigation water the model performed low leading to larger water supply (m^3) than is realistic.

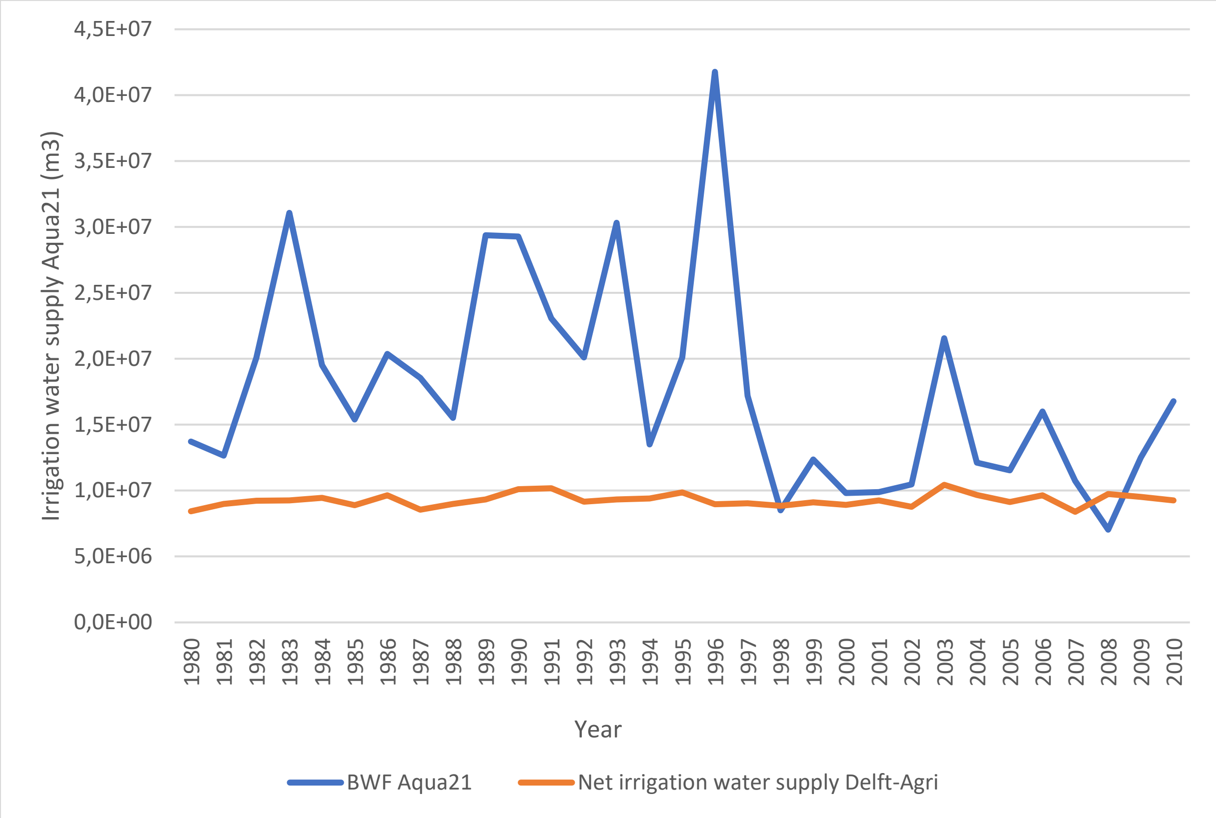

Figure 13: Yearly Blue Water Footprint (Aqua21) and Net Irrigation Water Supply (Delft-Agri) in m3 during the growing season for the Hochrhein

Table 7: Correlation between the Blue Water Footprint (Aqua21) and Net Irrigation Water Supply (Delft-Agri) for the five selected sub-basins.

	Main	**Hochrhein**	**Mosel/Saar**	**Bodensee**	**Neckar**
Irrigation water supply	0,12 (N=31)	0,25 (N=31)	0,19 (N=31)	0,24 (N=31)	-0,16 (N=31)

The third variable to estimate the model performance on is river discharge (m^3/s). This variable showed the performance of the RiBaSIM model. Figure 14 shows the river discharge (m^3/s) at Basel per 10 day time-step for the period 1990-2007. Both the simulated data by RiBaSIM, and the HYMOG validation data are plotted. At all four investigated gauges (Basel, Cochem, Mainz and Raunheim) the RiBaSIM discharge is larger than the HYMOG validation data. The pattern of both datasets is comparable, with higher discharges (m^3/s) during the winter period and lower discharges (m^3/s) during the summer period.

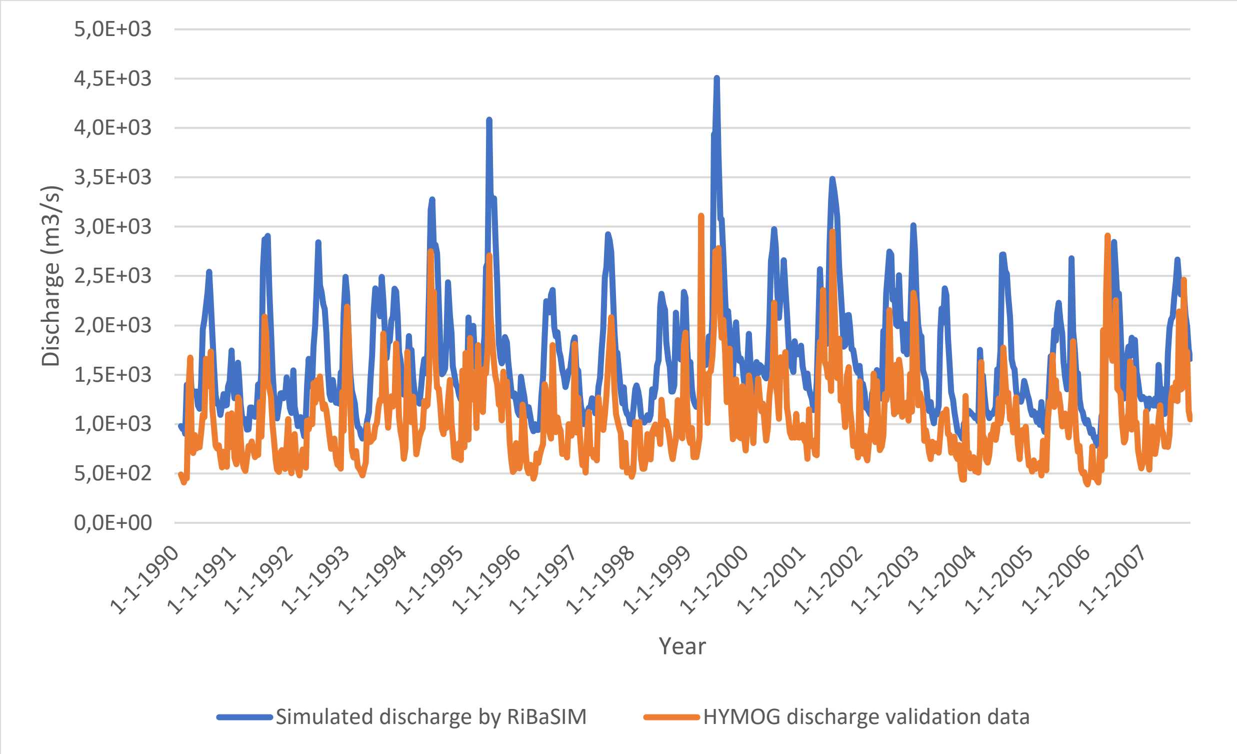

Figure 14: Discharge (m3/s) per 10 day time-step at Basel for the period 1990-2007

The NSE, RVE and correlation between the simulated flow (m^3/s) in RiBaSIM and the HYMOG discharge (m^3/s) validation data have been estimated and the results are shown in Table 8 per gauge. For all gauges 643 data pairs were used to estimate NSE, RVE and correlation. The NSE values range between -1.37 and 0.51, indicating low performance for all four gauges. For the gauges in the main river, at Basel and Mainz, NSE values are negative which means that the observed mean is a better predictor than the RiBaSIM model itself. The performance of the RiBaSIM model is also low in terms of RVE, for Basel the simulated discharge error value is more than 50%, which means that the simulated discharge is more than 50% higher compared to the HYMOG validation data. For the gauges at the side rivers, the performance is also low, but better compared to the gauges in the main river. The correlations are comparable and for all gauges correlation is high, indicating that the model performs well on recognizing the fluctuation pattern. For the gauges at side rivers (Cochem and Raunheim) correlations are slightly lower compared to gauges in the main river.

Table 8: NSE, RVE and correlation between RiBaSIM river discharge output (m^3/s) and HYMOG discharge validation data (m^3/s) for all years (period 1980-2010). Calculated with N=643 data pairs.

	Basel	Cochem	Mainz	Raunheim
NSE	-1,37	0,51	-0,86	0,07
RVE (m^3/s)	56,81	12,38	45,59	29,75
Correlation	0,80	0,75	0,76	0,75

In conclusion, the performance of the Delft-Agri model was estimated on the variables production (tonne), irrigation supply to the system (m^3) and river discharge (m^3/s). The performance of the production variable was low, since potential productions were reached all years and therefore the possible drought damage was not represented in the model outcomes, whereas in reality drought damage occurs. However, the related variable irrigation supply to the system (m^3) performed better, since fluctuations in water requirements over the years were noticed and BWF (m^3) and net irrigation water requirement (m^3) values for the year 2000 were comparable for most sub-basins. The third variable, river discharge (m^3/s), had low performance since the RiBaSIM model scored low on the NSE and RVE method. Nevertheless, correlations between the HYMOG validation data and the river discharge (m^3/s) were high, indicating that the model acted as the validation data in terms of fluctuation pattern.

4.3 Model performance in a dry year

4.3.1 Performance of Aqua21

The model output production (tonne), wet yield (tonne/ha) and harvested area (ha) of Aqua21 has been analysed for dry years, which have been marked in the figures in Appendix K with a triangle.

For the year 1996, there was missing data for most Bundesländer in the Aqua21 output data (for all three variables), which reduced the analyses of dry years to three years (1990, 1991, 2003). Besides, for the year 1991 there were outliers identified in the Aqua21 production output (tonne), these outliers can be traced back to the variable harvested area (ha), because in the yields data (tonne/ha) these outliers were not seen. This is showed in more detail for sugar beet in Baden-Württemberg. Figure 15 shows the yield data (tonne/ha) of sugar beet for Baden-Württemberg for the period 1980-2010. Here, it can be seen that there were no outliers in the data, whereas for production (tonne) outliers were identified (Figure 9). So, the outliers can be related to scaling to national statistics of harvested area (ha) data. That meant that in the analyses of dry years, the year 1991 gave a distorted view for the variables production (tonne) and harvested area (ha).

For the dry years it was expected that both production (tonne), as well as yield (tonne/ha) was lower than average years. For all Bundesländer this pattern was seen in the production validation data of both sugar beet and maize (Appendix K). The Aqua21 production output also showed this pattern for sugar beet and maize, especially for the dry year 2003. In 1990, the maize production output (tonne) of Aqua21 decreased, as expected due to the drought in that year, however the sugar beet production output (tonne) increased compared to the previous years. This was attributed to the harvested area (ha) data of Aqua21, because for maize the registration of harvested area changed from 1991 onwards, whereas the registration of sugar beet changed from 1990 (Appendix L). In 1991 a distorted view of the production output (tonne) of Aqua21 was noticed for both crops. But, when looking at the yield (tonne/ha) output of Aqua21 lower yields were seen for all dry years, Figure 15 shows this for sugar beet in Baden-Württemberg. The yield (tonne/ha) response of Aqua21 was in line with the validation data, both for average years as well as for dry years.

Overall, the production (tonne) was higher for Aqua21 than for the validation data in dry years. By interpreting the results of Aqua21 this has been taken into consideration. Also, in the Aqua21 production (tonne) output, there were lower productions noticed for certain years, which have not been identified as dry years in this study. An example is the production of maize for North Rhine Westphalia (Figure 41, Appendix K). This means that the drought indicators, which were used in this study, might not have been suitable indicators to determine drought.

In conclusion, the performance of the Aqua21 model for dry years was estimated on the variables production (tonne), harvested area (ha) and yield (tonne/ha). The estimation was constrained by lacking information in Aqua21 model output for the year 1996. Also, the harvested area dataset has been influenced by scaling to national statistics for the dry years 1990 and 1991. Nevertheless, the Aqua21 yield output (tonne/ha) was in line with the validation data for dry years. Also, the performance of the variable production (tonne) was in line with the validation data for the dry year 2003. Therefore, the performance of the Aqua21 model for dry years seemed to be good for the variable yield (tonne/ha). The variable production (tonne) showed a decrease, but the estimation is just based on one year (2003).

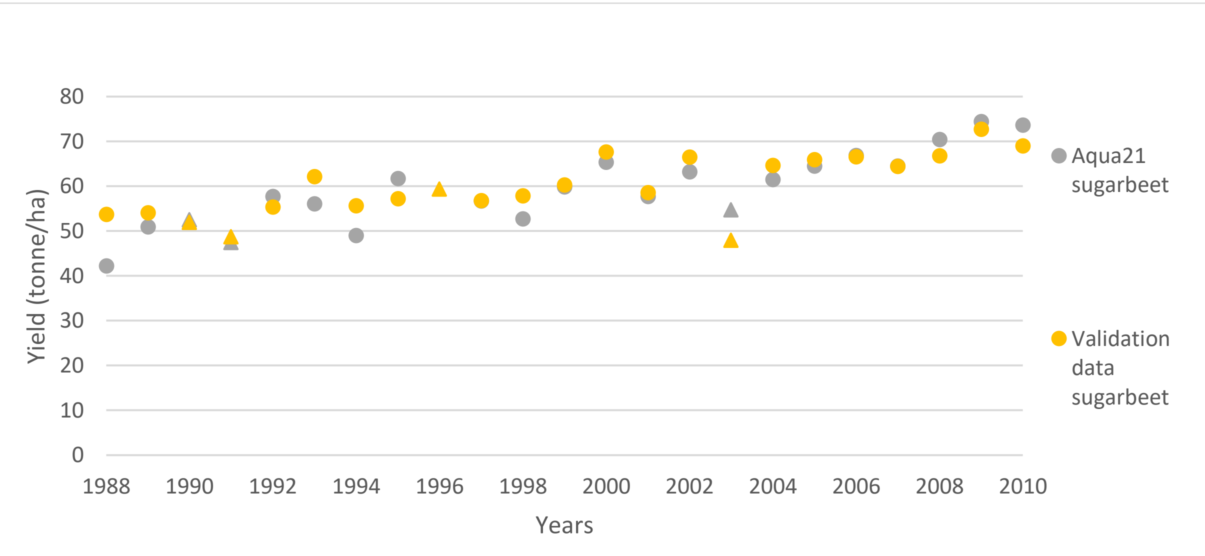

Figure 15: Yield tonne/ha of sugar beet for Baden- Württemberg for the period 1980-2010, dry years are marked with a triangle. Aqua21 data from the Aqua21 model (Hogeboom et al., 2020)*, validation data from Destatis* (Destatis, 2020b)

4.3.2 Performance of Delft-Agri

The performance of the Delft-Agri model for dry years has been tested with the output variables production (tonne), net irrigation water supply to the system (m^3) and river discharge (m^3/s).

For the production (tonne) variable, the potential production has been reached for every dry year for all analysed sub-basins for sugar beet and maize. That means that the Delft-Agri model is not yet able to simulate drought damage.

For the net irrigation water supply to the system (m^3) variable, it was expected that the supply is higher for dry years than for average years. Figure 16 shows the supply to the system for the Hochrhein and it can be seen that for the dry years 1990, 1991 and 2003 the supply (m^3) was higher than for the average years. Appendix M shows the supply to the system (m^3) and the BWF (m^3) for the other analysed sub-basins. The dry years 1991 and 2003 performed as expected, the supply increased compared to the average years, for 1990 this also happened but for some basins to a lesser extent. One clarification for this can be that the water demand was partly filled by infiltrated water in the soil during winter leading to a lower supply. Another clarification can be that the water demand was partly filled by rainfall: during the growing season there might have been more rainfall in 1990 compared to 1991 and 2003. The year 1996 does hardly respond. In the Aqua21 model there also was missing data (yield and harvested area data) for the year 1996, in the Delft-Agri model data errors might be in the rainfall data. When looking at the BWF (m^3) results for dry years, it is noticed that the BWF increased for all sub-basins during dry years, except for year 1996 in some sub-basins. The results for the year 1991 also are overestimations for some sub-basins, namely those sub-basins which have large land coverage in Germany. Overestimation is caused by scaling to national statistics of the harvested area data, which is influenced by the unification of West and East Germany in the year 1991.

The net irrigation water supply (m^3) and the BWF (m^3) values were not equal to each other for dry years, this might be caused by the use of one crop plan (based on the year 2000) for the whole simulation period for Delft-Agri. Also, the Delft-Agri model did not incorporate drought damage during dry years, leading to higher water supply than in reality would be the case, because in reality crops will die prematurely. Both models showed an increase in irrigation water supply (m^3) for dry years which is expected, however the Delft-Agri output might be overestimated.

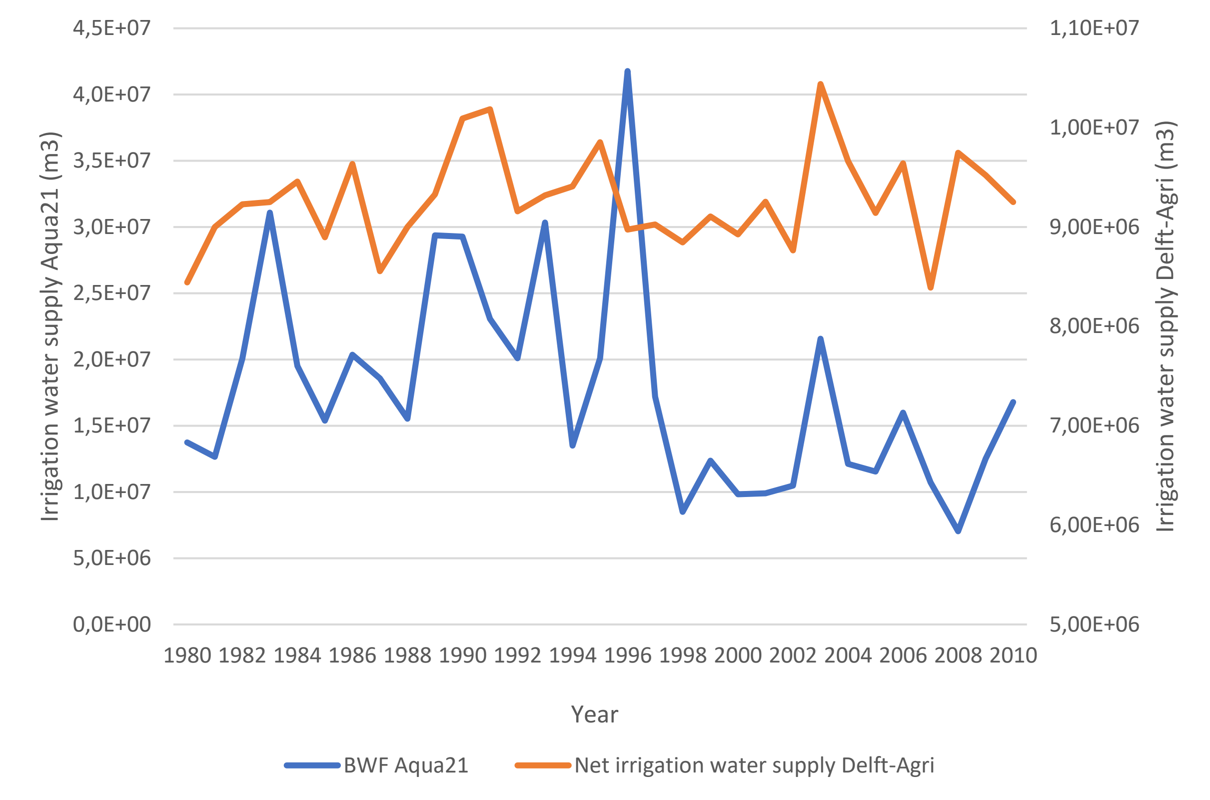

Figure 16: Yearly Blue Water Footprint (Aqua21) and Net Irrigation Water Supply (Delft-Agri) in m3 during the growing season for the Hochrhein, depicted with two axis.

The performance of the RiBaSIM model for dry years has been examined with the variable river discharge (m^3/s).

Table 9 shows the NSE, RVE and correlation between the RiBaSIM river discharge output (m^3/s) and the HYMOG validation data for dry years (1990, 1991, 1996 and 2003). For all four gauges, 144 data pairs were used to estimate the NSE, RVE and correlation. The NSE values for dry years were lower than for average years, which means that the RiBaSIM model performance on discharge (m^3/s) for dry years is extremely low. Also the RVE values for dry years were higher than for average years, meaning that the model performance was even lower for dry years compared to average years. For all four gauges, correlations were high, with Cochem and Raunheim performing highest. These two gauges are located at the side rivers, where fluctuations in river discharge are most visible. Because of higher fluctuations in dry years, correlations were higher compared to correlations for all years (Table 8). All in all, the performance of the simulated discharge (m^3/s) by the RiBaSIM model for dry years was low and RiBaSIM values were overestimated compared to the validation dataset.

Table 9: NSE, RVE and correlation between RiBaSIM river discharge output (m^3/s) and HYMOG discharge validation data (m^3/s) for dry years. Calculated with N=144 data pairs.

	Basel	Cochem	Mainz	Raunheim
NSE	-4,10	-0,48	-1,94	-0,64
RVE (m^3/s)	68,64	21,47	47,71	14,81
Correlation	0,79	0,83	0,79	0,86

In conclusion, the performance of the Delft-Agri model for dry years is estimated on the variables production (tonne), irrigation supply to the system (m^3) and river discharge (m^3/s). The performance of the production variable was low, since drought damage was not represented in the model outcomes. The related variable irrigation supply to the system (m^3) performed better, since peaks in water requirements over the dry years were noticed in both the BWF (m^3) by Aqua21 as well as the net irrigation water requirement (m^3) by the Delft-Agri model. However, the net irrigation water requirement (m^3) by Delft-Agri might be slightly overestimated due to not incorporating crops that die prematurely. The third variable, river discharge (m^3/s), had low performance for dry years since the RiBaSIM model scores low on the NSE and RVE method. Nevertheless, correlations between the HYMOG validation data and the river discharge (m^3/s) were high for dry years, indicating that the fluctuation pattern of the model results was similar to the validation data.

4.4 Scenarios

In this section, the fourth research question on plausible future agricultural scenarios in the context of increasing drought is answered. First, the scenario designs are explained (4.4.1), followed by the outcomes of the scenario simulations (4.4.2).

4.4.1 Scenario designs

In the scenarios two main dimensions of change were identified by the scenario panel and team that are expected to affect future irrigation water requirement: climate change and agricultural sectoral changes. The two dimensions both have two extremes (depicted in a spectrum, Figure 17): from *modest global warming* to *much global warming* (x-axis) and from *sustainable agriculture* to *intensive agriculture* (y-axis). The interpretation of the two dimensions on irrigated agriculture in the Rhine basin is explained in storylines, this is done for the year 2050.

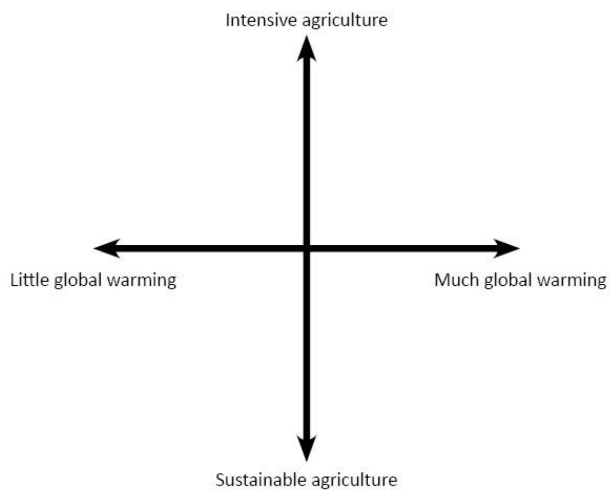

Figure 17: Spectrum of scenario design in this study, with on the x-axis climate change, on the y-axis agricultural sectoral changes

The climate change dimension ranges between modest and much global warming. In this study, *modest global warming* is considered by an increase in temperature of 1.1 degrees Celsius for the Rhine basin by 2050 compared to the reference period 1980-2010 (Lenderink and Beersma, 2015). This is based on the KNMI's GL (Gematigd Lage) scenario, which includes moderate temperature rise and low change in circulation pattern (KNMI, 2014). The increase in temperature will lead to an increase in evapotranspiration compared to the data of 1980-2010. The increase in evapotranspiration in the scenarios of this study is calculated with the help of the Blaney-Criddle method as described in section 3.4.2. In the scenarios of this study, a modest increase in global temperature does not lead to a change in rainfall by 2050 (Lenderink and Beersma, 2015).

The other extreme of the climate change dimension is *much global warming*. In this study, the WHdry (Warm Hoog) is considered, which includes a high temperature rise and high change in circulation pattern (KNMI, 2014). The scenario is called dry because high changes in circulation patterns are found to go along with drought conditions that may occur in future climate. It is particular characterized by a stronger reduction of precipitation in summer. Considered global warming in this scenario is 2.3 degrees Celsius by 2050 compared to the reference period 1980-2010. This will lead to an increase in evapotranspiration, which is calculated with the Blaney-Criddle method. Also, rainfall decreases during the months June, July and August with 17% compared to the reference period 1980-2010. Data for the Rhine basin on global warming and rainfall were based on the study of Lenderink and Beersma (2015) and applied in the scenarios of this study.

The agricultural sectoral change dimension ranges from *sustainable to intensive agriculture*. In this study, the sustainable agriculture focused on an increase in demand on products produced in the region. This raises possibilities for niche markets, such as regional and organically produced products

(Silvis and De Bont, 2005). In this scenario, also retailers sell more local products. The focus on export decreases, resulting in a decrease of export subsidies and import tariffs in the European Union on subsidized crops like potatoes, cereals and sugar beet (Silvis and De Bont, 2005; Provincie Limburg, 2006). It will lead to less production of these crops and therefore a decrease in acreage of agricultural land. This land will be bought to further enlarge the Nature 2000 structure and so achieve goals set in the 'Nature Directives' (Biodiversity, 2020). Furthermore, sustainable agriculture in this study is characterized by further enhancing green and blue services, such as water storage areas and increasing agricultural nature management (Planbureau voor de Leefomgeving, 2018), this is stimulated by providing subsidies. In this study, irrigated agricultural land was assumed to reduce by 20% under *modest global warming* conditions, versus 10% under *much global warming* conditions because under much global warming conditions irrigation of agricultural land was assumed to be more necessary due to a decrease in rainfall and an increase in evapotranspiration. Considering field management in the sustainability scenarios: irrigated agriculture shifts from no mulching to organic mulching (under full irrigation with sprinklers) in order to enhance the water productivity (Amarasinghe and Smakhtin, 2014 in Chukalla et al., 2015). This measure decreases the evapotranspiration by 17% during the growing season and was applied in the sustainability scenarios of this study (Chukalla et al., 2015). Also, in these scenarios, there is no social acceptance for genetically modified products, which means that the potential crop yield (Y_m) was assumed not to be changing in this scenario (Planbureau voor de Leefomgeving, 2018).

The other extreme in the agricultural sectoral change dimension is *intensive agriculture*. In this study, the *intensive agriculture* focused on increasing dependency on export, which is stimulated by innovation, social-cultural developments and governmental policy (Planbureau voor de Leefomgeving, 2018) (Silvis and De Bont, 2005). It is expected that the number of agricultural businesses decreases due to aging of farmers and them having no successors, and also because of the pressure to scale up businesses in this scenario, which is not possible for all existing businesses due to financial limitations or because farmers do not want to operate their business on a large scale (Provincie Limburg, 2006). It is expected that the total agricultural acreage remains the same, however it might be that some agricultural land changes into urban areas, while new agricultural land arises due to land reclamation, for example the Markerwaard in the Netherlands. Businesses that stay, increase in size and in their amounts of irrigated agricultural land (at the expensive of rainfed land). In this study, an increase of 10% of irrigated agricultural land was assumed under *modest global warming* conditions. Under *much global warming* conditions an increase of 20% was assumed, because under *much global warming* conditions irrigation of agricultural land was assumed to be more necessary due to a decrease in rainfall and an increase in evapotranspiration. In the *intensive agricultural* scenario there is social acceptance and a change of European guidelines (RVO, 2019) concerning genetically modified products. Products like potatoes will be resistant against phytophthora (potato disease), maize will be resistant against caterpillars. It was assumed that this leads to a further increase in crop production per hectare. In this study, the potential crop yield (Y_m) was increased for the four selected crops (sugar beet, potatoes, maize and oats) in the intensive agricultural scenarios. The Y_m values were determined by extrapolating the trend that is seen for Germany for the period 1980-2010 (Destatis, 2020b) till 2030, assuming that from then on there is no increase in yield. The values for 2030 were used for the whole simulation, since it is not possible to insert yearly Y_m values in Delft-Agri.

The two dimensions, climate change and agricultural sectoral change, induce four scenarios based on the dichotomies of 'export, intensive driven development' (S1, S3) versus 'regional, sustainable driven development' (S2, S4), and 'modest global climate change' (S1, S2) versus 'much global climate change' (S3, S4). An overview of the scenarios is given in Table 10. The four scenarios were based on a reference scenario, which is the scenario with the input variables as described in Table 4 and the irrigated crop plan as described in Table 2.

Table 10: Schematic overview of scenario designs for 2050 for the Rhine basin

Scenario S1: Modest global warming – Intensive agriculture *Precipitation:* data from the reference period 1980-2010. *Evapotranspiration:* increases, using the Blaney-Criddle method under 1.1 degrees warming. *Irrigated harvested area*: increase by 10% compared to the reference scenario based on the year 2000. *Yields*: increases, following the linear trend of the period 1980-2010 till 2030.	**Scenario S3: Much global warming – Intensive agriculture** *Precipitation:* rainfall is decreased by 17% for the months June, July, August compared to reference period 1980-2010. For the rest of the year data from the reference period 1980-2010 is used. *Evapotranspiration*: increases, using the Blaney-Criddle method under 2.3 degrees warming. *Irrigated harvested area:* increase by 20% compared to the reference scenario based on the year 2000. *Yields*: increases, following the linear trend of the period 1980-2010 till 2030.
Scenario S2: Modest global warming – Sustainable agriculture *Precipitation:* data from the reference period 1980-2010 *Evapotranspiration*: increases, using the Blaney-Criddle method under 1.1 degrees warming. And decreases by 17% due to the use of organic	**Scenario S4: Much global warming – Sustainable agriculture** *Precipitation:* rainfall is decreased by 17% for the months June, July, August compared to reference period 1980-2010. For the rest of the year data from the reference period 1980-2010 is used.

mulches. *Irrigated harvested area:* decrease of 20% compared to the reference scenario based on the year 2000.	*Evapotranspiration*: increases, using the Blaney-Criddle method under 2.3 degrees warming. And decreases by 17% due to the use of organic mulches. *Irrigated harvested area:* decrease of 10% compared to the reference scenario based on the year 2000.

4.4.2 Scenario results

In this section, the outcomes of the scenario simulations (both the reference scenario, as well as the four developed scenarios) are presented. The results of the reference scenario represent the current state of the irrigation water requirement and the impact on river flow. The other four scenarios represent the possible state of the irrigation water requirement and its impact on river flow for 2050. The simulations were done for a 30-years simulation period, including average years and dry years. The data that has been used is of the time period 1980-2010, with 1990, 1991, 1996 and 2003 being defined as the dry years of the simulation.

First, the yearly irrigation water requirement has been estimated for all scenarios for the Rhine basin. The estimated irrigation water requirements are the maximum irrigated water requirements, since the Delft-Agri model does not take into account a storm or plague, so crops can grow their full cycle without limitations. Figure 18 shows the yearly maximum irrigation water requirements (m^3) per scenario. The values of the year '2000' (it is the transformation of this year to a possible situation in 2050) were considered as most reliable since model performance for this year was good according to the validation with the BWF (m^3) (section 4.2.2). The *intensive agricultural* scenarios, had the highest water requirements and also showed high peaks during dry years, whereas the *sustainable agricultural* scenarios had lower water requirements and had less high peaks during dry years. As was expected, the *much global warming* scenarios had higher requirements than their *modest global warming* counterparts. In *modest global warming-sustainable agriculture* the water requirement (m^3) was even lower than the reference scenario for some years, which means that future water requirement (m^3) was expected to be lower than current water requirement (m^3). However, for dry years the water requirement in *modest global warming-sustainable agriculture* was still higher compared to the reference scenario. According to this study, water requirements (m^3) will increase in any case for 2050 when dry years are considered.

Since this study focused on dry years specifically, the year '2003' has been investigated in more detail. Figure 19 shows the monthly irrigation water requirement (m^3) of the simulated 2003. Large water requirement started from May, this is because then most crops are planted. In Delft-Agri water requirement for crops was high in the time step of planting (Van der Krogt, 2008). In August water requirement (m^3) was also high due to less rainfall and high evapotranspiration, in the current situation irrigation water requirement is $9.4*10^7$ m^3/month. The *intensive agricultural* scenarios had the highest water requirements (m^3) in all months, with an increase of 96% (under *modest global warming*) to 130% (under *much global warming*) by 2050 during the growing season compared to the current situation. The *sustainable agricultural* scenarios did not deviate much from the reference scenario, compared to the current situation an increase of 12% (under *modest global warming*) to 33% (under *much global warming*) can be expected by 2050. In order to not require more irrigation water from the system in 2050 (under global warming) compared to the current situation, organic mulches can be used, as well as a decrease in the use of irrigated agricultural land should be aimed for according to the results of this study.

In this study, the type of agriculture, *intensive* versus *sustainable*, had more influence on the water requirement (m^3) than the climatic variable (the influence of changing precipitation and evapotranspiration).

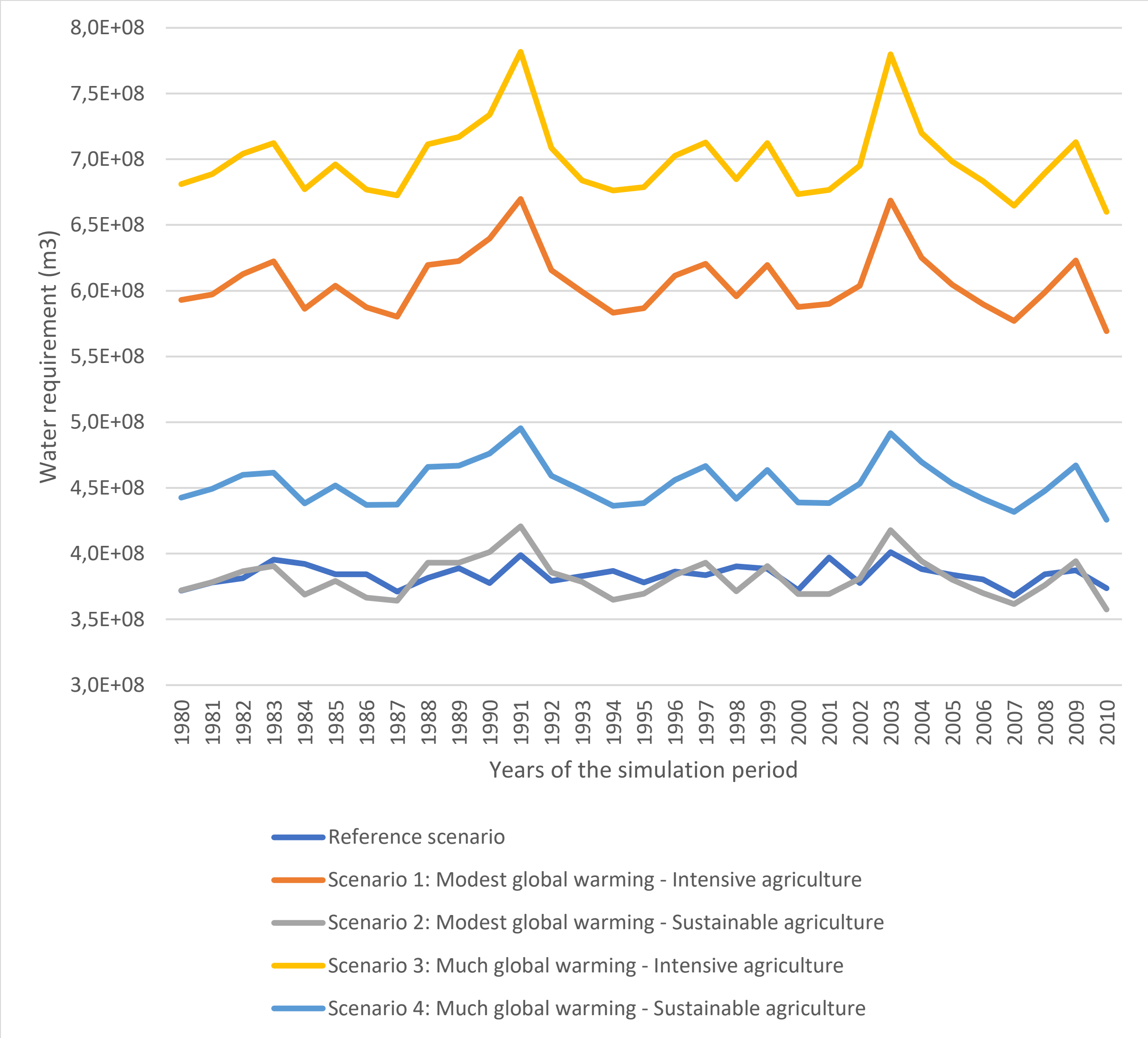

Figure 18: Yearly irrigation water requirement (m³) of the Rhine basin during the growing season per scenario over a simulation period of 30 years

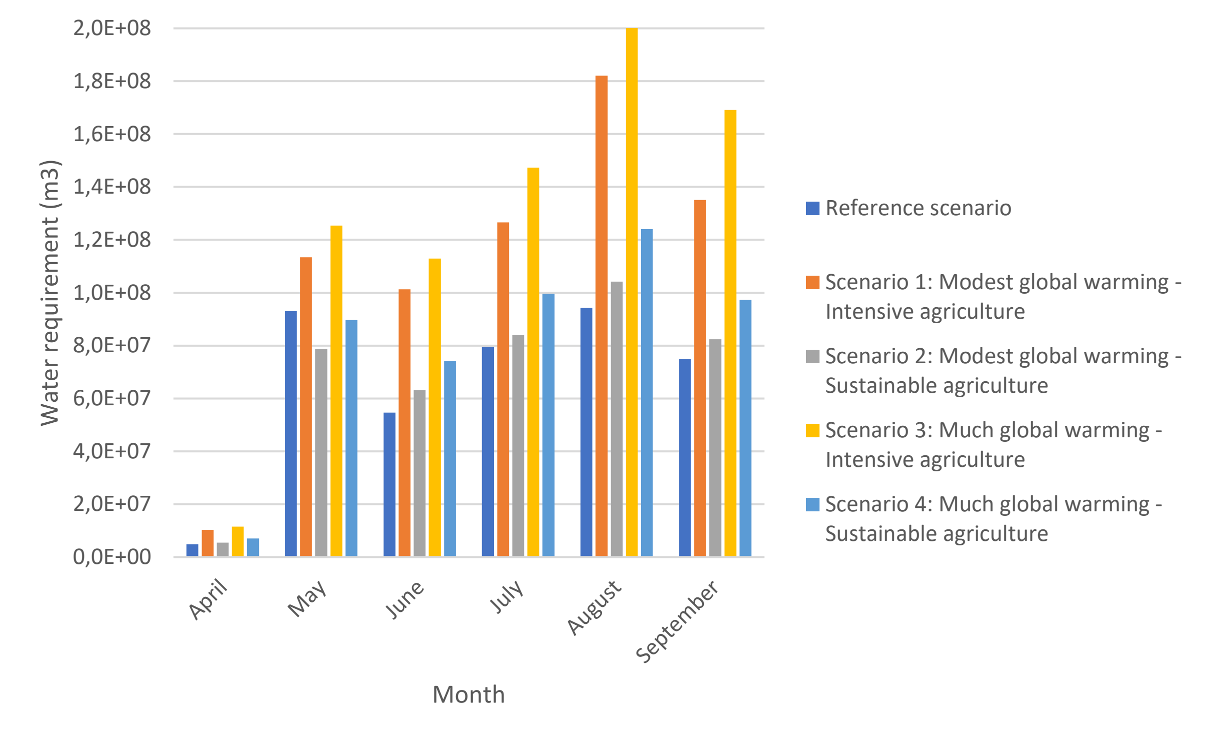

Figure 19: Monthly irrigation water requirement (m^3) for the Rhine basin during the growing season for the dry year "2003" per scenario

The impact of the irrigation water requirement (m^3) on river flow (m$^{3/}$s) was estimated for the gauge at Raunheim, which is located in the side river Main. Figure 20 shows the yearly river flow (m$^{3/}$s) decrease at Raunheim during the growing season per scenario as a percentage of river flow in the reference scenario. It should be taken into consideration that the decrease in river flow (m$^{3/}$s) due to global warming was not incorporated, and was only due to changes made in irrigated agriculture as described in Table 10. It became clear that the changes made in this study in Delft-Agri do not have a large impact on changing river flow (m$^{3/}$s). For all years and all scenarios, changes in river flow relative to the reference scenario remain below 1%. This was also seen for the other three gauges considered in this study (Cochem, Mainz and Basel). This means that irrigated agriculture has small influence on the discharge of the side rivers as well as the total discharge of the Rhine.

Figure 20 does show that river flow (m$^{3/}$s) will reduce in 2050, since for all years the percentage is negative compared to the current situation. For dry years, river flow (m$^{3/}$s) in 2050 will be for sure lower than the river flow in the current situation according to this study. Figure 20 also shows that the changes in the agricultural sectoral scenarios are significant relative to the climate change scenarios.

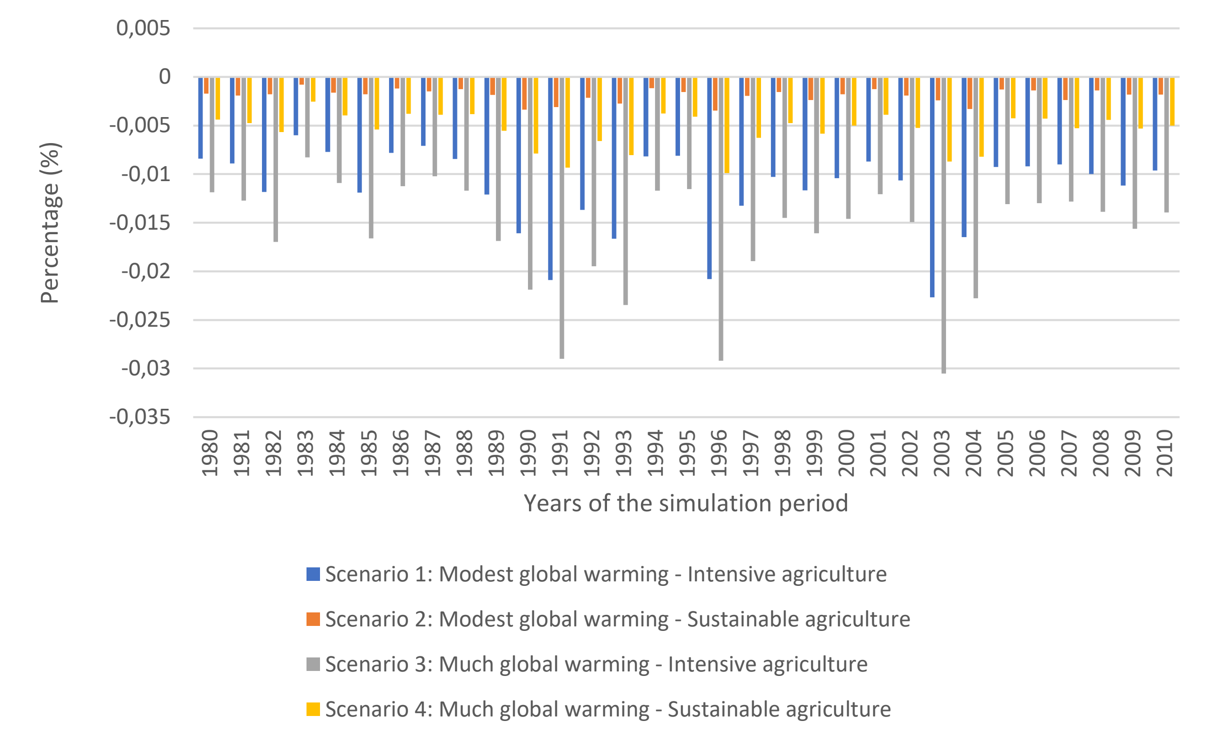

Figure 20: Yearly river flow at Raunheim during the growing season per scenario as a percentage of the reference scenario

For all scenarios, all crops and all sub-basins actual production (tonne) was equal to potential production (tonne). This means that all water that is demanded, can be delivered which means there is no under delivery in supply. Therefore there is no competition over irrigation water in this study.

In conclusion, the irrigation water requirement (m^3) was highest for the *intensive agricultural* scenarios. The *much global warming- intensive agriculture* scenario had the highest irrigation water requirement of all four considered scenarios. When considering dry years, the possible irrigation water requirement was especially large in August when evapotranspiration is high and precipitation low. The impact of the irrigation water requirement (m^3) on river flow (m^3/s) was limited according to this study, however the study did not consider decreases in river flow caused by climate change.

5. Discussion

5.1 Validation of research design

In this study, the current and possible future irrigation water requirements of the agricultural sector in the Rhine basin during the growing season in periods of drought and their impacts on river flow were estimated. Although focus was put on the Rhine basin, the same research approach and models (Aqua21 and Delft-Agri) can be used for any other basin. In this case, the schematization of the basin in RiBaSIM, including its inputs variables (Figure 7) has to be changed.

The crops sugar beet, oats, potatoes and maize were included in the present study since they are responsible for the majority (>95%) of irrigation water requirement in the basin according to the Aqua21 model (Hogeboom et al., 2020). In Aqua21, irrigated cropland for main crop types were derived from the MIRCA2000 dataset developed by Portmann et al. (2010), who established a global database for around the year 2000. Minor crops are used from the database provided by Monfreda et al. (2008), which also covers the year 2000. For other years than the year 2000, the Portmann/Monfreda base map is masked by the irrigated cropland extent from HYDE (Klein Goldewijk et al., 2011) and HID (Siebert et al., 2015). Due to the uncertainty in the base map on (irrigated) harvested area (ha) data per crop in the dataset by Portmann/Monfreda, it could be that in reality a different crop is grown than the Aqua21 map shows. This uncertainty is therefore also reflected in other years. Furthermore, the actual agricultural area might also change over the years, which is not reflected in the Aqua21 model. Another uncertainty may lie in that certain crops are irrigated, such as beets for fodder or grasslands, but registered by the FAO in different crop categories per country, so they are not represented well in the Aqua21 model.

Also, the Aqua21 model gives insights in the total irrigation water use on a global scale with the help of national statistics of harvested area and yield data, the outcomes of Aqua21 should be interpreted with care if used on a smaller scale than the country level.

The focus of this study has been on dry years. Dry years were classified as such using the drought indicators cumulative rainfall, which is an indicator for meteorological drought, and discharge deficit, which is an indicator of hydrological drought. Combined, these indicators show the impact on agricultural drought, which is the drought in the top soil. When meteorological drought and hydrological drought occur at the same time, possibilities to irrigate are limited and agricultural drought arises (KNMI, 2018). However, other drought indicators could have been used in this study such as rainfall deficit, the amount of soil moisture or the water storage in reservoirs, possibly resulting in other dry years. Nevertheless, the drought indicator cumulative rainfall in this study accounts for the not replenished water levels during winter and so takes into consideration the developments in the calculations of drought, since a lack of water replenishment during winter is expected in the future (KNMI, 2020b).

The design of this present research, in terms of testing the performance of both models, knows two limitations. The first limitation is the validation on two crops instead of four, yet maize and sugar beet cover a large part of both the irrigated harvested area (ha) (depicted in Figure 2), as well as the irrigated and rainfed harvested area (ha) together in the Rhine basin (depicted in Figure 54, (Appendix N)). Therefore, they were deemed to be sufficiently representative to test the model performance on. The second limitation on testing the performance relates to the number of data pairs used for the estimation of the correlation of production output data (tonne) for Aqua21. For some Bundesländer only 16 data pairs were available to estimate correlations on due to lacking validation and Aqua21 output data. For these Bundesländer only limited statements can be made about the model performance.

For the design of the scenarios of this study, the SAS approach is used. This approach is costly since it requires the organisation of many meetings, and the participation costs of the team and panel (Alcamo, 2001). It also is a time-consuming approach because it calls for multiple cycles of scenario review. In this study, step 9 and 10 of the SAS approach (which include the general review of scenarios by experts and stakeholders and the revision of the scenarios) were not taken into account because of time constraints. For future research, the credibility and legitimacy of scenarios, and consequently the results, can be further improved by including stakeholder and expert review sessions during the SAS stage.

5.2 Interpretation of results

5.2.1 Aqua21 model

The performance of the Aqua21 model is tested, among other things, with the help of the correlation method applied on the production (tonne) variable. The production variable, however, arises from multiplying the harvested area (ha) variable and the yield (tonne/ha) variable and therefore consists of two variables, which makes it difficult to trace back the performance results. However, the underlying variables have also been analysed in this study in order to account for their performance. Therefore, conclusions could be drawn from the correlation values of the production (tonne) variable.

This study tested the performance of the global Aqua21 model on a regional (NUTS-1 level) scale. It became clear that the harvested area (ha) dataset of Aqua21 is not homogeneous over the period 1980-2010 due to specific aspects of the scaling to national statistics. In this study, this relates to the unification of Germany in the period 1990-1993. Scaling of the harvested area (ha) dataset to NUTS-1 level data (the validation data used in this study for Germany) would lead to more accurate results.

Furthermore, the harvested area (ha) dataset of Aqua21 contained missing data for the years 1984 and 1996, limiting the analysis of dry years from four to three dry years (since 1996 was defined as a dry year). In addition, regarding the analysis of average years, missing data led to a smaller N to estimate correlations on. However, there still was a sufficient amount of data pairs to estimate correlation and therefore the performance of the production (tonne) variable could be estimated, which turned out to perform good for average years. Also, the performance of this variable turned out to be good for dry years, based on descriptive statistics.

5.2.2 Delft-Agri model

In the production (tonne) results of Delft-Agri, potential productions are achieved every year. There are several possible causes for this, which need further investigation. One of the causes could be the distribution of the irrigation nodes, since in Delft-Agri each sub-basin has one irrigation node in which surface water of the whole basin is accessible. However, in reality irrigation areas are distributed over the sub-basin leading to smaller upstream areas with limited access to surface water, possibly leading to limitations in crop production (tonne). Another reason might be the absence of a defined environmental flow in the RiBaSIM model. Because no environmental flow is considered, irrigation water can be extracted from the river to a physically infeasible large amount. Also, it could be that the Delft-Agri model is to a limited extent sensitive for a change in precipitation, this might be caused by not considering the hydraulics of water movement in the root zone.

By interpreting the results of the Delft-Agri model for the period 1980-2010, it should be taken into consideration that the crop plan used is a static one in which only the year 2000 is considered. This limits the analysis of the performance of the Delft-Agri model. Likewise, in relation to the scenarios a static annual crop plan is also not expected, since crop ratios will change over the years. Changing crop ratios also lead to changing water requirements over the years, and so to better approximations of the actual water requirements. The same holds for the potential crop yield (Y_m), which is also treated in a static manner in Delft-Agri, although it is dynamic in nature. In this study, Y_m is based on national statistics of Germany (Destatis, 2020b), an average of the period 1997-2002 has been used as this period covers the year 2000. Y_m has been determined by multiplying the corresponding national average yield values per crop by a factor of 1.2 as has been done in Mekonnen and Hoekstra (2011b). Because there is no specific Y_m value for each year, factors that improve yields such as crop breeding and fertilization are not taken into account in the modelling scheme. Although in the real case the Y_m value changes over the years, in the modelling scheme the Y_m value is simplified, leading to an overestimation of Y_m in the *much global warming* scenario, since the Y_m value will drop when the Rhine basin faces meteorological and hydrological drought.

The irrigation water requirement estimations of this study are maximum requirements since all planted crops can grow their full cycle and will not die prematurely due to a plague or storm since this has not been incorporated in the Delft-Agri model.

The results of the current monthly water requirements (m^3) as estimated in this study (as depicted in Figure 19, reference scenario) are put in perspective to the Rhine001 study. This study shows monthly average values that are 30% lower compared to the Rhine001 study. Since the Rhine001 study is a first attempt and this study is more elaborated, the results of the Rhine001 study can be considered as an overestimation. Also, the pattern over the months is different, whereas in this study the peaks of water requirements (m^3) are in the months May and August, the Rhine001 study shows peaks in May and June (Deltares, 2019). The peaks in May can be explained by the large water demand in the time step of planting as modelled by Delft-Agri (Van der Krogt, 2009). The earlier peak during the growing season in the Rhine001 study (June instead of August) can be explained by the limitations in crop input variables such as the crop coefficient K_c in the Rhine001 study. So, the estimations on irrigation water requirements as done in this study, are an improvement compared to the Rhine001 study.

Concerning water use in the scenarios, behavioural change and political decisions have not been taken into account. It might be that farmers in *intensive agriculture* will invest in (synthetic) mulches or water-saving irrigation technology under *much global warming* conditions leading to a decrease in their water consumption, if that would be economically attractive. Likewise, it might be that under *much global warming* conditions water extraction bans may be introduced for the agricultural sector, resulting in a decrease of irrigated harvested area (ha). Another factor that has not be taken into account in the scenarios is the decrease in river flow ($m^{3/}s$) caused by climate change.

6. Conclusion

This study aimed to estimate the current and possible future irrigation water requirements of the agricultural sector in the Rhine basin and with that the impacts on river flow of the Rhine during the growing season. The irrigation water requirements are estimated with the help of the Aqua21 and Delft-Agri model. Aqua21 is a crop growth model with a focus on plant growth processes to determine crop yield and water use, whereas Delft-Agri is a water demand and allocation model focusing on water availability at a certain place and time. Aqua21 includes more input variables on environmental conditions (such as CO_2 concentration and temperature) in order to simulate the possibilities for plant growth, than the Delft-Agri model. Also the processes within the models differ, for the estimation of evapotranspiration the Aqua21 model focuses on canopy cover, whereas Delft-Agri uses linear interpolation methods between the growth stages. The processes in the soil also differ, Aqua21 includes hydraulic movement within the soil, whereas Delft-Agri does not. However, Delft-Agri, which is focusing on water availability, incorporates a peak in water requirement when a crop is planted, whereas Aqua21 does not.

The insights in the functioning and differences between both models help to interpret their model results. For Aqua21, the model performance is good for yield (tonne/ha) and production (tonne) output data. High correlation values for the production (tonne) data are seen for maize, especially for the Bundesland North Rhine-Westphalia. The performance of the harvested area (ha) variable is limited due to the heterogeneity of the dataset. The Delft-Agri model does not show drought damage for the irrigated crop plan as implemented in this study, since sufficient water is available. The Delft-Agri model performs good for the net irrigation water requirement (m^3) variable. The performance of the RiBaSIM model package is estimated with the help of discharge data (m^3/s). Yet, performance is rather low, with overestimations in river discharge (m^3/s).

Since this study focuses on periods of drought, the model performance for dry years is also determined. Aqua21 responds to dry years in the model output by showing lower productions (tonne), however the production (tonne) output of Aqua21 is higher than the validation data. This suggests that Aqua21 slightly overestimates productions (tonne) for dry years. The Delft-Agri model shows an increase in net irrigation water supply (m^3) to the system for dry years, as well as the BWF of Aqua21 does. However, the Delft-Agri outputs might be slightly overestimated due to not incorporating crops that die prematurely.

The study shows that the current irrigation water requirement of the agricultural sector in the Rhine basin during the growing season in periods of drought can go up to $9.4*10^7$ m^3/month. This irrigation water requirement considers the whole river basin for the month August, however differences between sub-basins and differences between months were seen. Figure 2 shows that the largest irrigated harvested areas (ha) are located in the sub-basins Main and Oberrhein, meaning that these two sub-basins contribute most to the irrigation water requirement. Figure 19 also shows the differences in irrigation water requirement (m^3) between months during the growing season, with August showing a peak, meaning that this month contributes most to the irrigation water requirement.

The possible future irrigation water requirement of the agricultural sector in the Rhine basin during the growing season in periods of drought varies per scenario. For the *intensive agricultural* scenarios an increase of 96% (under *modest global warming*) to 130% (under *much global warming*) can be expected during the growing season for the year 2050. The *sustainable agriculture* scenarios show an increase of 12% (under *modest global warming*) to 33% (under *much global warming*) compared to the current scenario.

The impact of the irrigation water requirement (m^3) on river discharge ($m^{3/}s$) under the various scenarios is rather low. However, this study did not consider decreases in river flow caused by climate change.

7. Recommendations

Based on the conclusions and regarding the notes of the discussion in chapter 5, a number of recommendations are made for further research into future water availability and for further use of the Aqua21 and Delft-Agri model.

For further research it is important to have better estimations on irrigation (mm) data and irrigated harvested area (ha) data, for example by carrying out remote-sensing research. By doing so, irrigation water use (from groundwater and surface water) might be available on NUTS-1 level. In this way, Aqua21 irrigation (mm) data and irrigated harvested area (ha) data can be scaled to these statistics, which will further improve the reliability of the model outcomes.

Alternatively, since collecting new data is rather time-consuming and costly, improvements on water requirement estimations can also be done with existing data. An example is the scaling of Aqua21 irrigated harvested area (ha) data per crop to the irrigated harvested areas (ha) as determined in the Rhine001 study (Eurostat, 2019). This is a valid approach, since the Rhine001 dataset includes information on land use on NUTS-1 level.

Given that irrigation water requirements are strongly related to water availability and water distribution, it would be relevant for future research to link the water requirements estimated for several scenarios in this study to the water distribution issue. The impacts of climate change on water availability should then first be taken into account. By doing so, more insights will be gained into the size of possible water shortage problems, also taking into account the impacts on the environmental flow. Furthermore, insights can be gained on possible environmental damages caused by water shortages and how to prevent them.

Recommendations regarding the models are mainly focussed on Delft-Agri. A first addition that can be made in the Rhine RiBaSIM schematization is the implementation of groundwater nodes. In the current schematization, no groundwater nodes are implemented. This means that the demand nodes, such as the advanced irrigation node and the public water supply node, cannot be supplied by groundwater but just by surface water in this specific model. In reality, however, water is also extracted from groundwater. A second addition that can be made is the inclusion of the capillary rise variable, because it will complete the soil water balance, resulting in better water requirement estimations. Lastly, in order to get a more complete picture of the total irrigation water requirement per crop, more crops should be added to the Delft-Agri model including the option to implement an annual crop plan.

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Appendices

Appendix A: Determination of crops

The Rhine basin is a relatively wet basin: the average yearly rainfall in the basin is 969 mm per year, the average yearly soil evaporation is 273 mm per year. When including the transpiration in the basin the total evapotranspiration comes to 664 mm on average per year (Hogeboom et al., 2020). Despite it is a wet basin, some crops are being irrigated. An analysis of the average amount of irrigated water per type of crop per year in the Rhine basin (Hogeboom et al., 2020) for the period 1980 - 2010 is made (Figure 21). The volume of average irrigation water (m^3) is calculated by multiplying the irrigated harvested area with the irrigation parameter (Figure 22 and Figure 23 respectively). Figure 21 shows that sugar beet consume most irrigated water on average per year, 2852 m^3, followed by oats which consume on average yearly 1587 m^3 of irrigated water, potatoes consume 1420 m^3 and maize 760 m^3 (Hogeboom et al., 2020). These crops cover more than 95% of the total irrigation in the Rhine basin. Therefore, these are selected in this study. To cover the rest of the basin in the Delft-Agri model, the remaining 5% of the area is filled as if it would have been 'apples', because this is the next largest irrigation water consuming crop.

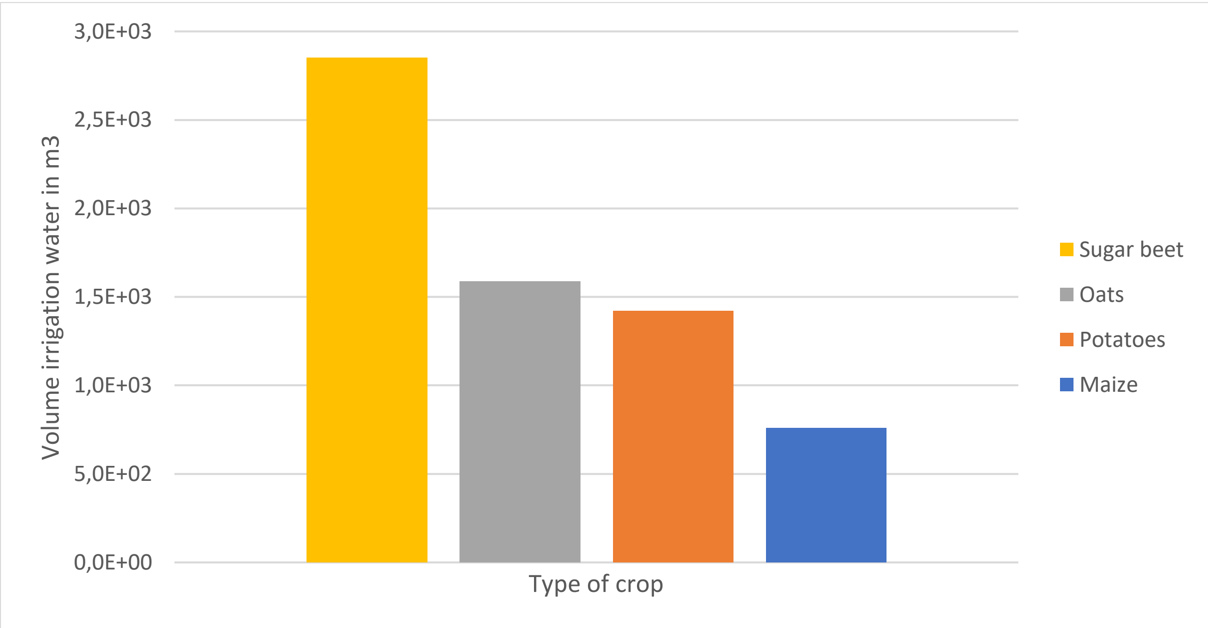

Figure 21: The four largest crops in terms of average irrigated volumes (m^3) in the Rhine basin over the period 1980-2010 (Hogeboom et al., 2020)

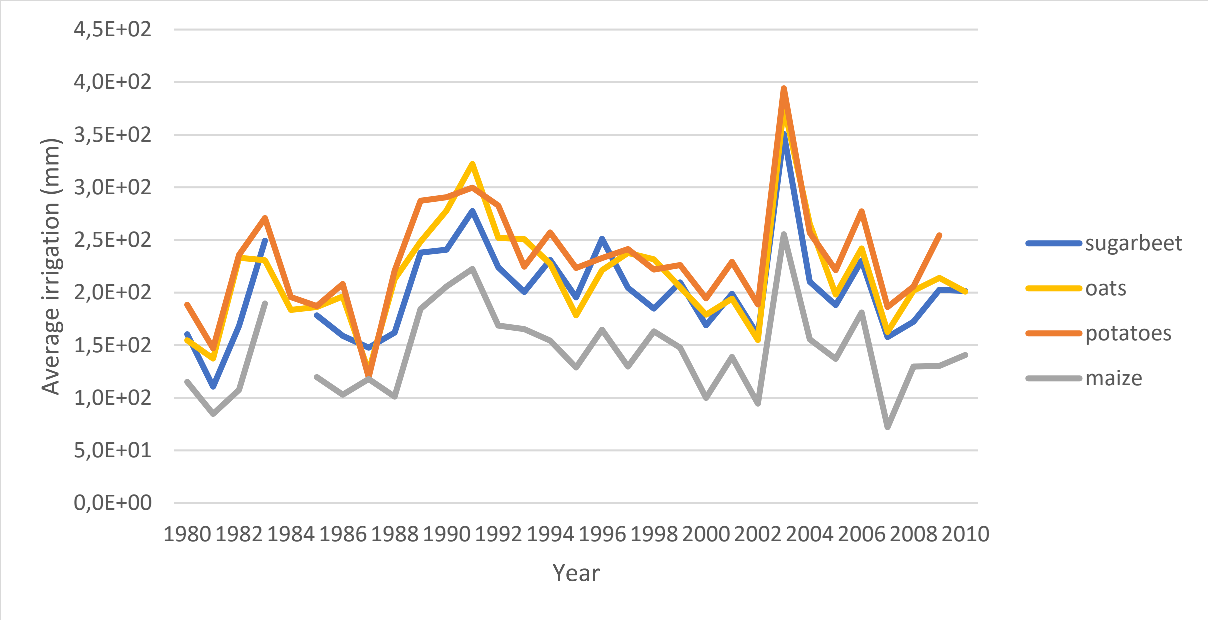

Figure 22: Average irrigation in mm per year for the period 1980-2010 for the Rhine basin (Hogeboom et al., 2020).

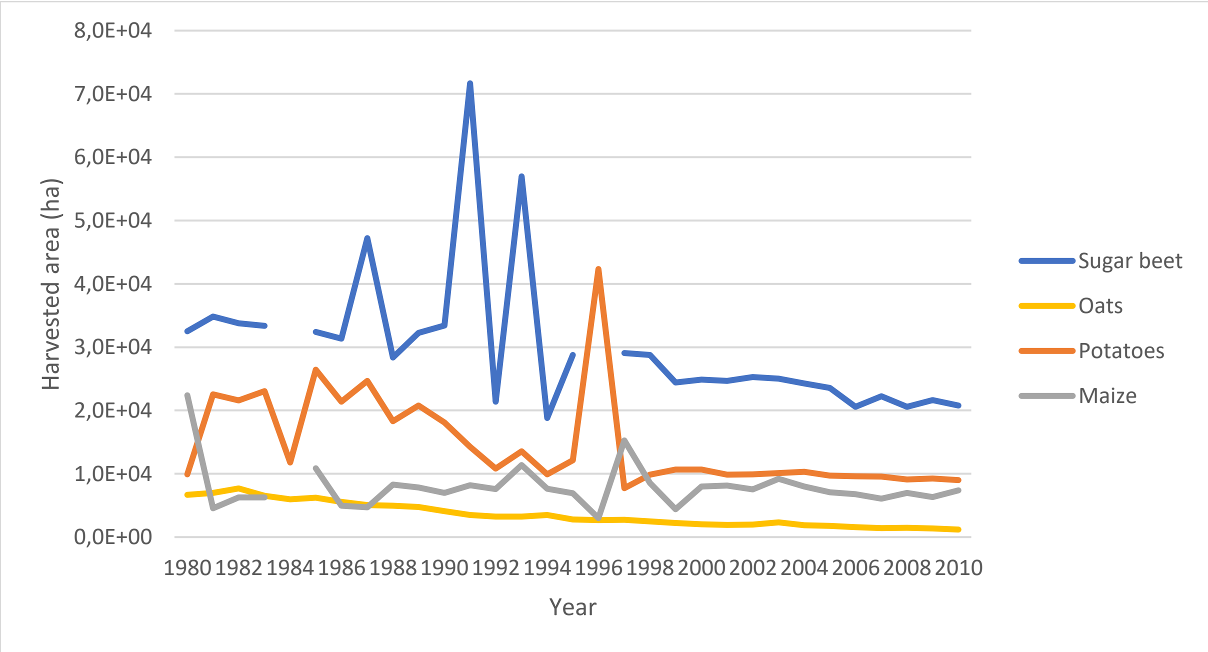

Figure 23: Irrigated harvested area in ha per year for the period 1980-2010 for the Rhine basin (Hogeboom et al., 2020).

Appendix B: The Water Footprint Concept

The water footprint is a concept developed by Arjen Y. Hoekstra in 2002 (Hoekstra, 2003) to quantify the freshwater use of a consumer or producer. It looks at both the direct, as well as the indirect water use, respectively the operational water to produce the product and the volume of freshwater used to produce the product, measured over the whole supply chain (Hoekstra et al., 2011).

The water footprint knows three components: the blue, green and grey. The blue refers to consumption of blue water resources, such as surface and groundwater, along the supply chain. Green water footprint refers to the consumption of green water resources, such as rainwater. Grey water footprint deals with pollution and the volume of freshwater that is needed to assimilate the load of pollutants (taking into account natural background concentrations and water quality standards) (Hoekstra et al., 2011).

In this study, the blue and green water footprint are taken into account, because these are of importance when considering crop water-use in the Rhine basin and are therefore included in the Aqua21 model (there is no grey water footprint in the Aqua21 model). Crops consume water to grow, and this water comes from rain (green water) and from surface and ground water (blue water). Figure 24 shows the green and blue water footprint of a catchment, in this case the Rhine basin can be considered, the catchment is fed with precipitation which partly infiltrates into the soil and vegetation and partly runs off at field level, where it becomes ground and surface water. Within the catchment evapotranspiration (ET) takes place, which can be divided into non-production-related evapotranspiration and production-related evapotranspiration. When the latter -the human use of the evaporative flow- is considered, the term green water footprint can be used. Also, the rain water taken up and hold by the crops relates to the green water footprint. The blue water footprint refers to the consumptive use of the run-off flow. Water ‘consumption’ means the loss of water from the available ground and surface water in the catchment area. Losses take place when water evaporates (production-related), returns to another area or the sea or when it is incorporated in a product (Hoekstra et al., 2011). When the water is abstracted, but returned into the catchment within the same period, there is no footprint.

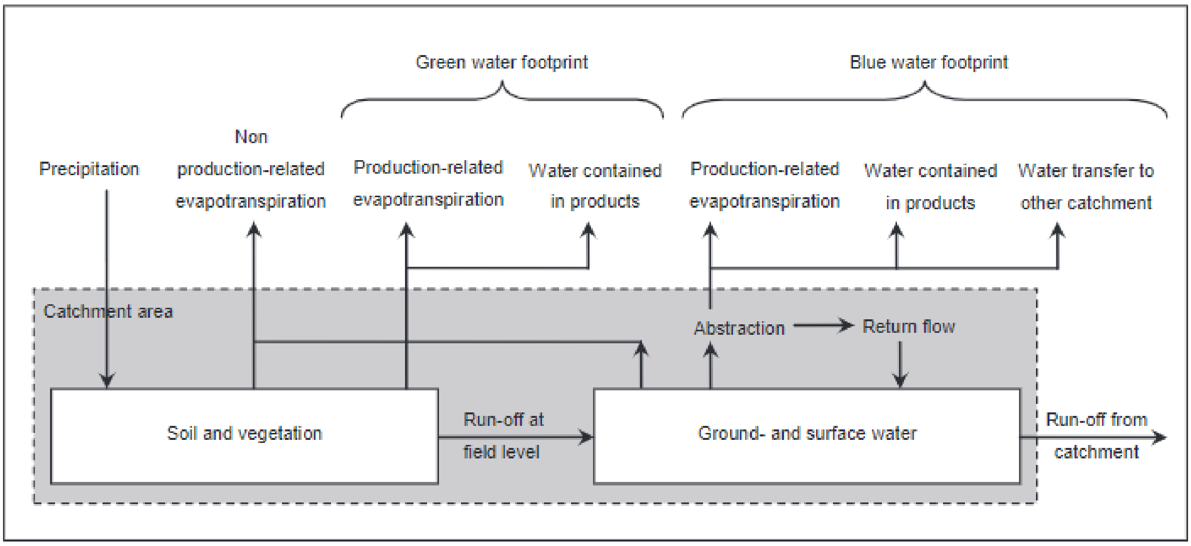

Figure 24: Green and blue water footprint in relation to a catchment (Hoekstra *et al.*, 2011)

Appendix C: Crop growth simulation model AquaCrop

C.1: AquaCrop flowchart

Figure 25 shows the overall structure of AquaCrop's main components in a flowchart (Raes, 2016). It shows the four steps to calculate yields (further explained in Appendix C.2), the input variables (as explained in Appendix C.3) and the relations between them.

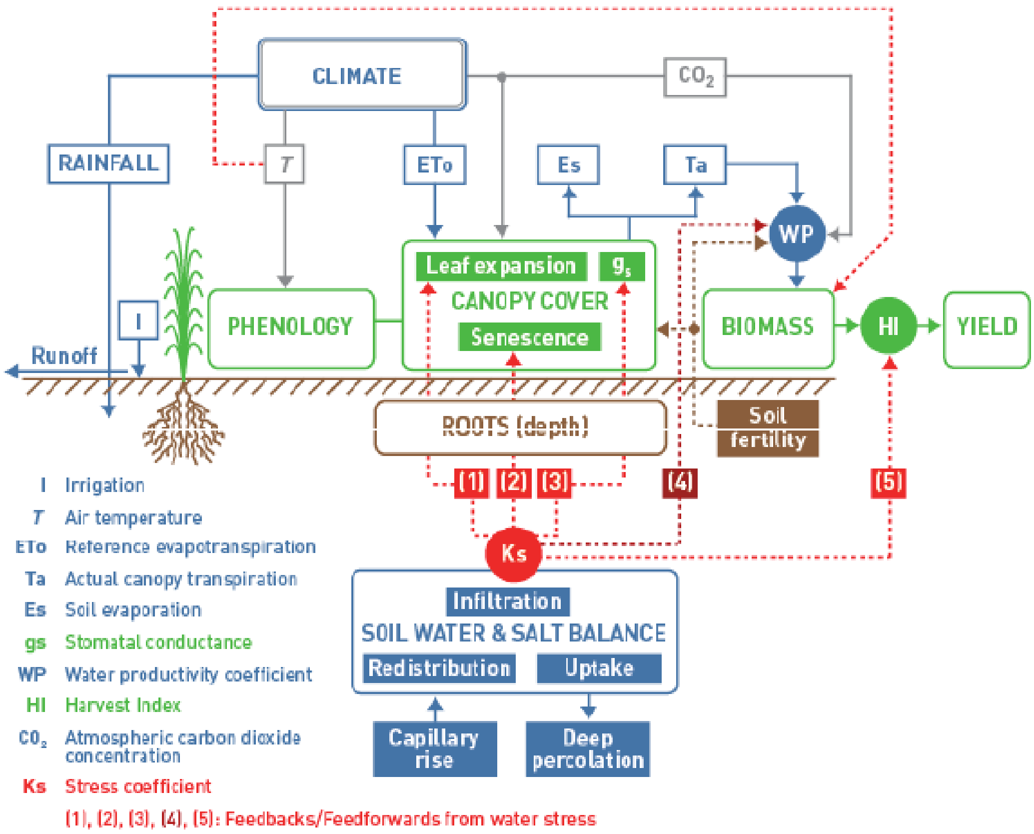

Figure 25: Flowchart of the main components of the soil-plant relations within the AquaCrop model (Raes, 2016)

C.2: Four steps to calculate yield

AquaCrop uses four steps to simulate crop yield, the steps and formulas are shown in Figure 26. The steps are explained here:

1. Determining the development of the green canopy cover (CC), this is the fraction of the soil surface covered by the canopy, with 0 being no canopy cover (at sowing) and 1 being full canopy cover (mid-season). Other models use the leaf area index instead of CC, however CC offers a simplification in the simulation by using a sigmoid function (S-shaped curve) and so reducing the canopy development with time. Senescence of the canopy is also simulated, but then with a decline function (Raes, 2016). Both, canopy development and canopy senescence,

are determined by the water content in the soil profile, if stresses occur in the root zone, canopy reduction is simulated. If no stresses occur, canopy expansion is simulated (FAO, 2020a). Another factor that influences CC expansion and CC senescence is temperature, AquaCrop simulates this influence by correcting the WP and HI (Vanuytrecht et al., 2014).

2. Is about the transpiration of crops, crop transpiration (Tr) is calculated by multiplying ETo (reference evapotranspiration) and KcTr (crop coefficient). The crop coefficient is dependent on the CC value, cause the canopy is changing throughout the life cycle. In well-watered conditions, the Tr is at its maximum, however when stresses occur in the soil, stomata in the crop can close and directly affect Tr (FAO, 2020a). The stresses are expressed through stress coefficients (Ks), examples of stresses are: canopy senescence, canopy expansion, stomatal control of transpiration/stomatal conductance (gs) (Raes, 2016).
3. Above-ground biomass (B): calculated by the cumulative amount of Tr multiplied by the water productivity. Within the model, WP is normalised for influences in the environment of the crop such as climatic conditions, seasons and concentrations of CO_2 (measured at Mauna Loa Observatory, Hawaii). Also, WP is partially affected by fertility levels (Raes, 2016).
4. Crop yield: part of the biomass (B) is the actual yield (Y), therefore the harvest index (HI) is used, which is the fraction of B that is harvestable. HI is determined by adjustments on the HIo (reference harvest index), due to stress effects on the crops (FAO, 2020a). Y then is calculated by multiplying B and HI. HI increases over time (from pollination to physiological maturity) in an almost linear way (Raes, 2016).

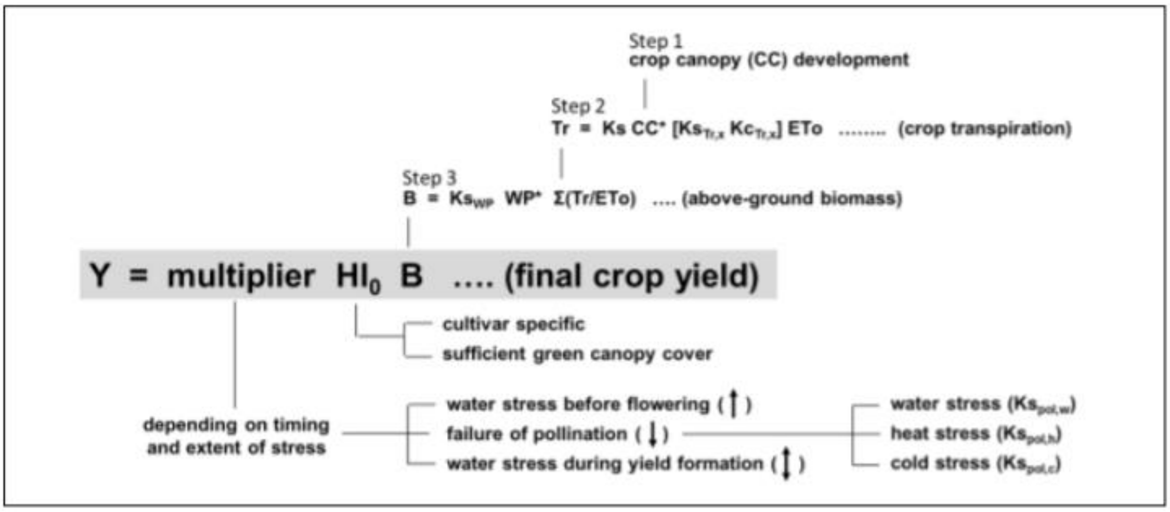

Figure 26: Calculation method of the Yield by AquaCrop (Raes, 2017)

C.3: Input data AquaCrop

Figure 27 shows the required input data for the AquaCrop model. Data on climate, crop, soil and management is needed (FAO, 2020a). A further explanation per input variable is given in Table 11.

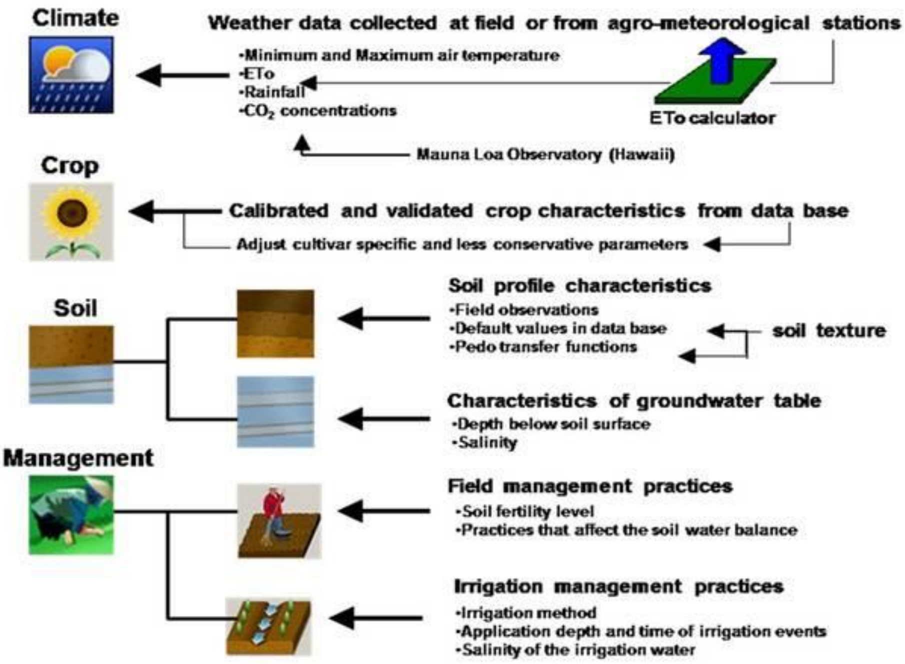

Figure 27: Input variables AquaCrop (FAO, 2020a)

Table 11: Required input for simulations with AquaCrop; table is literally copied from (FAO, 2016b)

Input variable	Comments
Climate (conditions at the upper boundary):	
Daily, 10-daily or monthly maximum and minimum **air temperature**;	The required climatic data is for one or more years. Daily data will be generated by AquaCrop at run time, if the climate files contain 10-daily or monthly input data is given.
Daily, 10-day or monthly mean values of **Reference evapotranspiration** (ETo), or of climatic data to compute ETo. (AquaCrop contains a calculator in which data can be givens in a wide variety of units to estimate ETo). The required data to calculate ETo can consist of air humidity, wind speed, and radiation or sunshine data;	
Daily **rainfall data** (10-day or monthly mean not recommended although better than none);	

Mean annual **CO_2 concentrations**.	Historical data from Mauna Loa Observatory (Hawaii) and various sets (with different storylines) of expected [CO_2] for future years, are available in the database of AquaCrop.
Crop parameters likely to require adjustments for cultivar and local environment and management:	
Planting date;	AquaCrop can generate planting date from rainfall, air temperature data, or soil water content in top soil.
Plant density;	AquaCrop can estimate plant density from plant spacing, or from seeding rate and germination percentage.

Maximum canopy cover (CCx);	Depending on plant density and cultivar. Can be easily observed in the field.
Time to crop emergence, flowering, start of canopy senescence and to maturity (length of crop cycle);	Cultivar specific. Can be easily observed in the field.
The proportion of grain dry weight to above- ground biomass, i.e., harvest index (HI);	
Maximum effective rooting depth (Zr_x) and time to reach Z_x.	Depends on conditions in root zone.
Soil physical parameters of the distinctive (up to 5) soil horizons:	
- Soil water content (θ) at saturation, field capacity, and permanent wilting point; - Saturated hydraulic conductivity; - Depth of layer restricting/limiting root deepening.	A hydraulic properties calculator (Saxton and Rawls, 2006) is available to estimate θ’s and Ksat from soil texture. From θ_{SAT}, θ_{FC}, θ_{PWP} and Ksat, AquaCrop derives other physical parameters governing soil evaporation, internal drainage, deep percolation, surface runoff and capillary rise
Groundwater table (Conditions at the lower boundary):	
Depth and salinity of the groundwater table (if less than 4 meter below root zone)	Can be constant or variable in time. Field data
Field management practices:	

Soil fertility: Indication of the maximum relative dry aboveground biomass (Brel) that can be expected in the fertility-stressed environment compared to stress-free conditions;	Brel is the maximum B that can be produced under the governing local conditions in a field only affected by soil fertility stress in a good rainy year or under irrigation when there is no water stress. It may be available from statistical reports, indigenous farmer knowledge, or from nearby experimental fields.
Practices affecting soil evaporation and/or surface runoff (mulches, tied ridges, soil bunds): - Cover and type of soil mulches; - Height of soil bunds; - Adjustment of surface runoff when affected by crop type and planting	Field data; Guidelines are available in the 'Field management menu' of AquaCrop.
Irrigation management practices:	
Irrigation method;	The method affects soil evaporation. Field data.
Application depth and time of irrigation events; Salinity of the irrigation water.	Field data.
Initial conditions at start of simulation period:	
Initial soil water content and soil salinity at various depths in the soil profile.	In the absence of measurements or sampling of the soil profile at the time of sowing/planting, measurements or samples collected earlier can be used to determine the initial soil water content. In this case the simulation should start before the sowing/planting day and the simulation period is no longer linked with the growing cycle. In the absence of any measurement or sampling, the initial soil water content needs to be estimated. For example: - Soil profile will be close to Field Capacity at the end of a winter period characterized by ample rainfall and a small to negligible evaporative demand of the atmosphere; - Soil profile will be close to Wilting Point at the end of a summer period characterized by the absence of rainfall/irrigation and a high evaporative demand of the atmosphere (with a reference evapotranspiration (ETo) of 5 mm/day or above).

Field data (for calibration/validation)	
- Maximum green leaf area index (LAI) or crop canopy cover at various times over the season; - Above ground biomass at various times over the season and at crop maturity; - Final yield at crop maturity.	With the help of the light interception function, LAI can be converted to CC: $CC = 1 - e^{-k \, LAI}$ where k is a crop specific growth coefficient (~ 0.7).

Appendix D: Delft-Agri model

D.1: Phases in the RiBaSIM model per time step

The simulation in RiBaSIM proceeds in time steps. For each time step the water balance is computed based on the supply of water, the demand of water by the various users, the operation rules for the various structures like surface water reservoirs and weirs, and the water management policies on basin level. The supply and demand of water is schematized with the help of nodes, the types of nodes are prioritized (Table 12) (Van der Krogt, 2008).

Table 12: Default source priority list of RiBaSIM (Van der Krogt, 2008)

Default order in the source priority list	Type of nodes
1	Groundwater reservoir
2	Fixed, variable and advanced irrigation Fish pond Groundwater district Public water supply General district
3	Variable and fixed inflow
4	Surface water reservoir

In each time step the water allocation is carried out priority wise. Every node goes through two phases: the target setting phase and the allocation phase (Figure 28).

In the target setting phase or demand phase, three steps are processed (1) inventory of demands, (2) inventory of available water, (3) computation of the target releases (Van der Krogt, 2008). The inventory of demands is done for each node. For some nodes, such as the advanced irrigation node the demand is computed based on various input parameters. After this step the model knows how much water is required for each node of the network. The inventory of available water is determined for each source node. A computation of the target releases is done to see if the available water satisfies the demand. Target releases are done from surface water reservoirs, groundwater reservoirs and with diverted flows (Van der Krogt, 2008).

During the allocation phase water is routed through the network of nodes and links in a downstream direction (the direction is set in the simulation sequence). All demand nodes (Table 12) are prioritized, with priority 1 the highest priority. The water is first allocated to all demand nodes with priority 1, followed by priority 2 and so on. By doing so, the water shortages occur at the lowest priorities. Within each priority the water is distributed from upstream to downstream, this way the water shortages occur at the most downstream users (Van der Krogt, 2008). However, a more detailed water allocation is possible by dividing the demand node into two parts with each a different priority. In case the upstream flow is not big enough to satisfy the demands, adjustments of demands are made. Adjustments are made in the nodes that do not have a priority, the 'unaddressed' nodes, which can act both like source nodes as well as demand nodes such as the groundwater reservoir and surface reservoir nodes. If water shortage occurs, then the target is adjusted and water is asked from the unaddressed source nodes. In case of water surplus, the target is adjusted and water 'enters' the node (Van der Krogt, 2008).

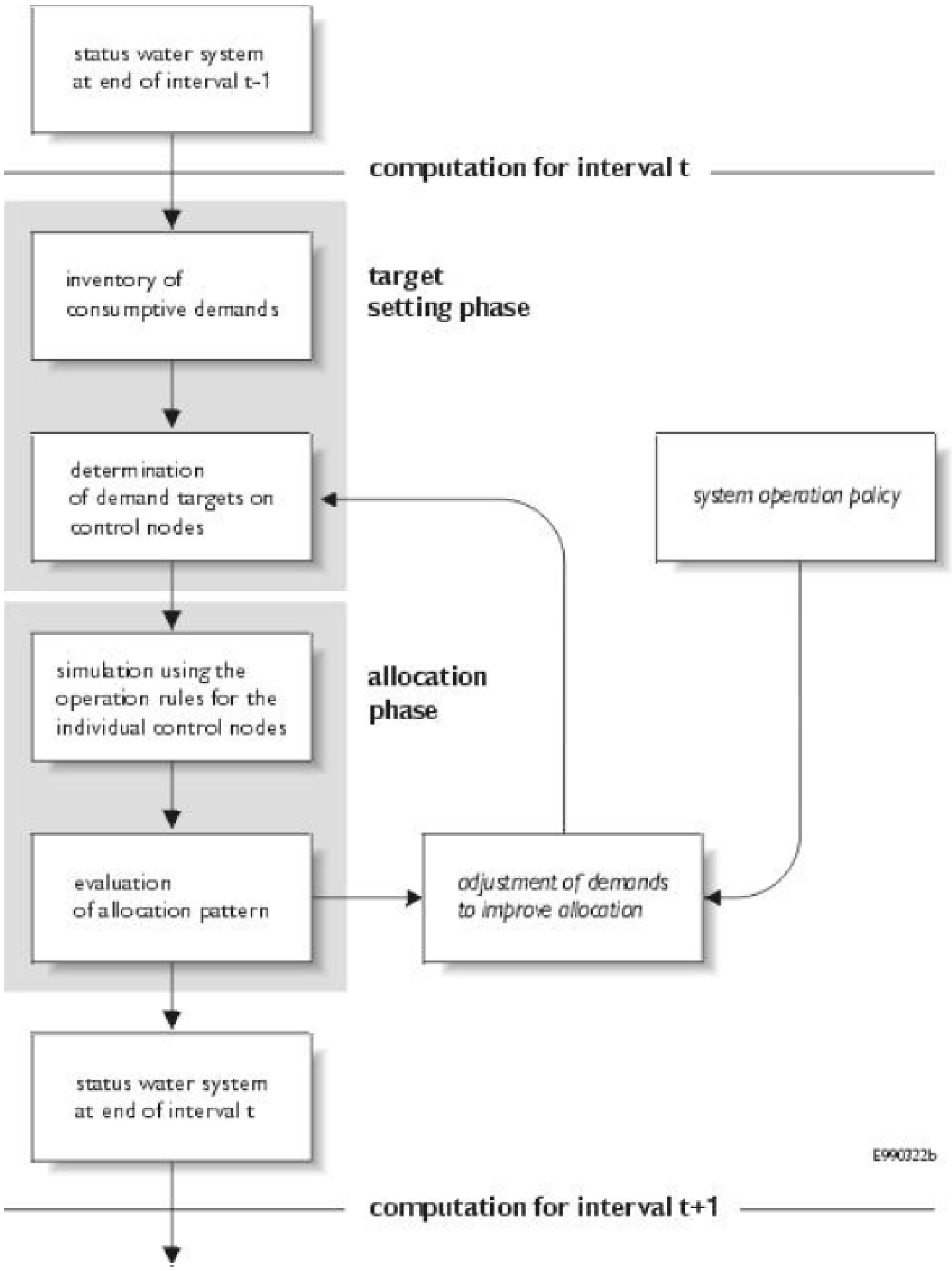

Figure 28: Overview of the phases in a time step in the RiBaSIM model (Van der Krogt, 2008)

D.2: Irrigation nodes of Delft-Agri

The agricultural module in RiBaSIM, Delft-Agri, is represented by four type of nodes ((1) Fixed irrigation node; (2) Variable irrigation node; (3) Advanced irrigation node; (4) Groundwater district node) which are explained here:

1. The first node is a fixed one, it is a simple type of node and allows simulation of a cropping pattern. The input is a net unit water requirement (mm/day) per time step, the input is used for all simulation years, no matter if it is a dry or wet year. The water source can be surface water or groundwater (Van der Krogt, 2008).
2. The second node allows more variability and takes into account the expected rainfall: the more rainfall is expected, the less water is required from the network. The amount of effective rainfall is set as a fixed percentage of the expected rainfall. The expected rainfall and actual rainfall are separate input files. The expected rainfall can be equal to the actual rainfall, but can also be equal to the dependable rainfall time series. The sources of this node are: actual rainfall, surface water or groundwater. Rainfall is the first source, if there still is remaining demand, the other sources are consulted (Van der Krogt, 2008).
3. The advanced irrigation node makes it possible to compute agricultural water demand, allocation, crop yield and production costs. In order to model this, the following input is needed: actual crop plan; crop characteristics; hydrological input; soil characteristics; topography and lay-out of the scheme; operation and water management of the scheme; crop yield and production costs parameters (Van der Krogt, 2008). The node distinguishes two different crop types: dry-land crops (like vegetables) and flood basin crops (like paddy). The source of water can be field buffer storage, actual rainfall, surface water or groundwater. The first source is the field buffer storage and the rainfall. If there is remaining demand, the other sources are used.
4. The groundwater district node computations are similar to the variable irrigation node. The water source can be surface water or local groundwater. Priority of the sources can be indicated (Van der Krogt, 2008).

D.3: Crop plan editor Cropper

In the graphical crop plan editor Cropper, the cropping pattern can be defined. Figure 29 shows a crop-time diagram and associated water balances for planned cultivations. In this example cropping patterns are defined per sub-basin with a 10-day time step period.

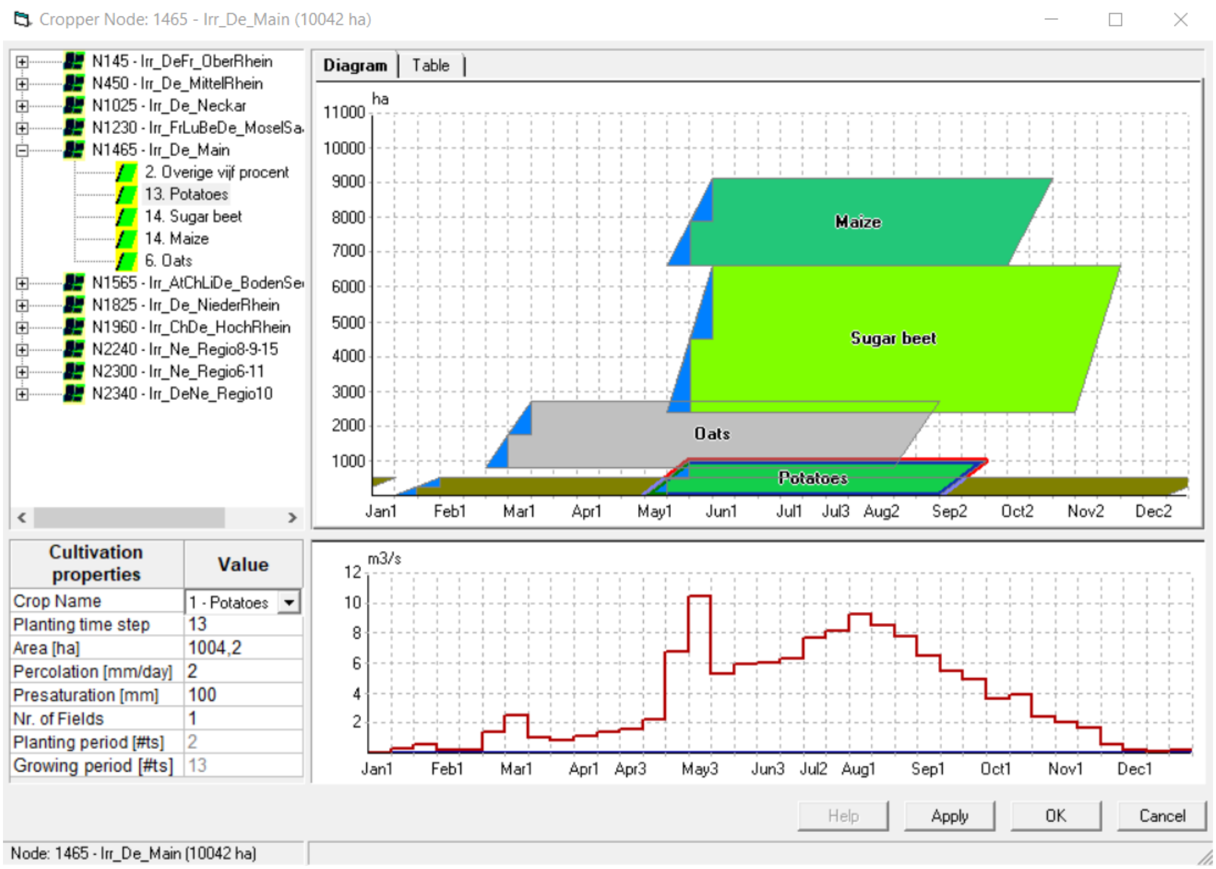

Figure 29: Crop-time diagram and associated water balances for planned cultivations (Van der Krogt, 2008)

Appendix E: Sub-basin division of the Rhine basin

Figure 30 shows the sub-basins of the Rhine catchment. Also a map of NUTS 1 level is added as a background map and is labelled by a land code and number (Eurostat, 2020).

Figure 31 shows the water management areas and the five adaptation areas for the Netherlands. This division is made based on water origin and management. The water management areas are combined into adaptation areas to easily implement Delta decisions (Ter Maat and Vat, 2015).

Figure 30 and Figure 31 are combined in determining the resolution of the Rhine RiBaSIM model. The Rhine RiBaSIM model is schematized on sub-basin level (as shown in Figure 30). However, an extra sub-division is made for the Deltarhein: it has been divided into the adaptation areas Rivierengebied and Benedenrivierengebied (Figure 31).

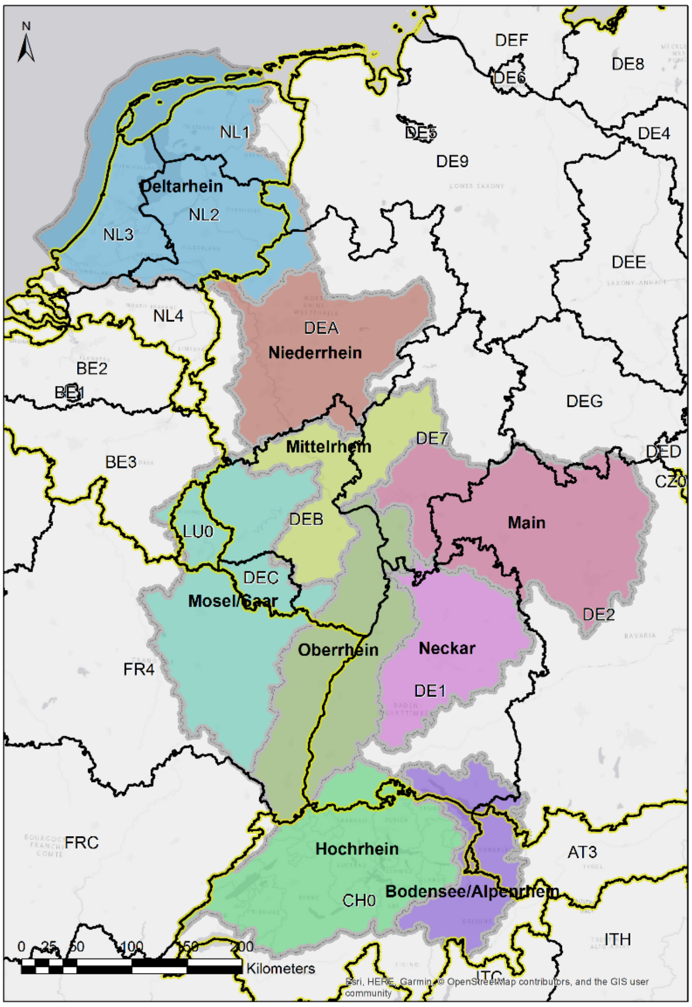

Figure 30: Division of sub-basins within the Rhine catchment. Also, NUTS 1 level is presented as a background map with a land code and number NL = Netherlands, BE = Belgium, LU = Luxembourg, FR = France, DE = Germany, CH = Switzerland, AT = Austria, IT = Italy (Deltares, 2020a)

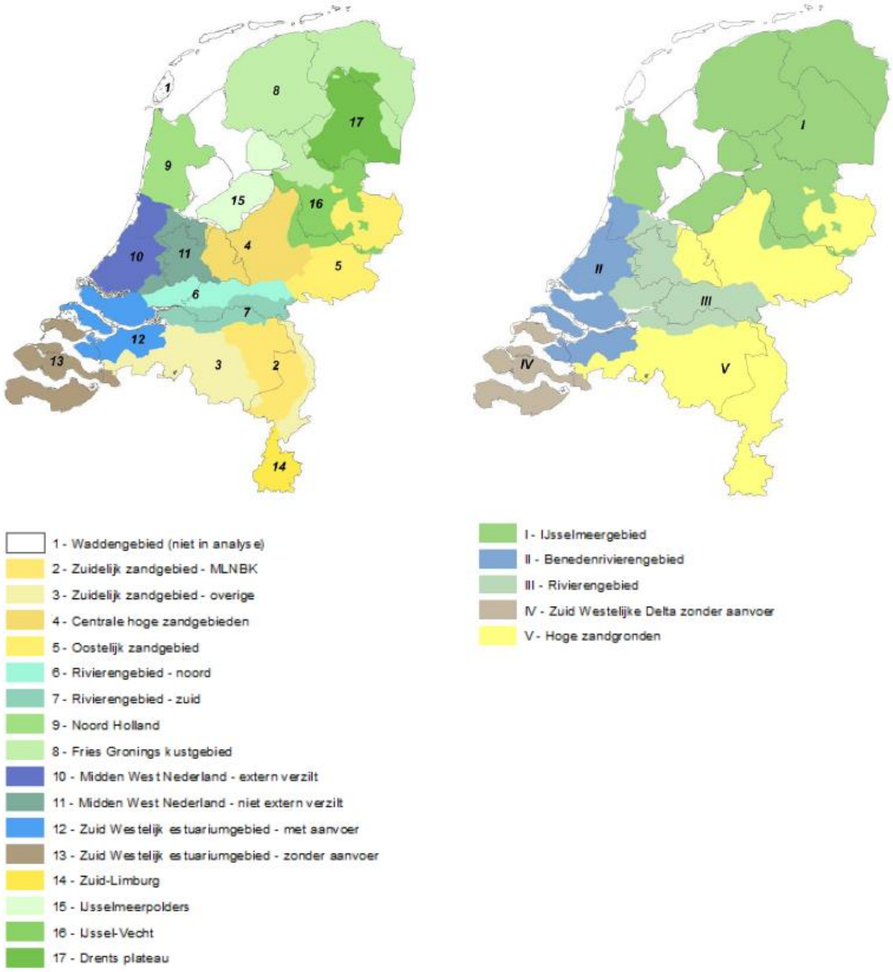

Figure 31: Water management areas (left) and the five adaptation areas (right) (Ter Maat and Vat, 2015)

Appendix F: Gauges of the HYMOG project

Figure 32 shows the gauges considered in the HYMOG project (The international Commission for the Hydrology of the Rhine basin, no date; Steinrücke et al., 2012). In this study the gauges Cochem, Raunheim, Mainz and Basel are considered.

Figure 32: Gauges of the HYMOG project (The international Commission for the Hydrology of the Rhine basin, no date; Steinrücke et al., 2012)

Appendix G: Aqua21 input variables

The variables that are used in this study are listed in Table 13. The variable name, unit, interpretation and the source of the variable are shown.

Table 13: List of variables of the Aqua21 model, the interpretation of the variables is included, as well as the source of the variable for this research (Hogeboom *et al.*, 2020)

	Variable	**Unit**	**Interpretation**	**Source**
Crop production	Atmospheric CO2 concentration	ppm	Annual CO2 concentrations for the period 1902-2099. CO2 concentrations are not spatially distributed, so one value per year suffices globally for all cells	AquaCrop inventory
	Minimum and maximum temperatures	^{0}C	The Utrecht dataset consists of average temperatures, so the CRU TS3.21 monthly diurnal temperature ranges were taken, were divided by two and added and subtracted by the daily average temperatures to get max. and min. temperature values.	(Van Beek et al., 2011)
	Growing areas per crop per country per year	ha	Based on reports on the harvested area by the FAO. The modelling exercise in Aqua21 is a downscaling procedure for these national statistics to grid-based levels	(Aquastat, 2015)
	Planting and harvesting dates	day	Aqua21 makes use of fixed dates instead of modelled dates based on climatology. Instead, data by (Portmann, Siebert and Döll, 2010) is used whereby sowing takes place on the first day of the month and harvesting the last day of the month.	(Portmann et al., 2010)
	Length of phenological stage	day	Growing degree days are assigned, instead of fixed calendar days, to account for spatial variability in climate growth stages.	AquaCrop inventory
	Soil depth	m	1 m across the globe: top soil of 0.3 m and subsoil of 0.7 m thickness	(De Lannoy et al., 2014)
	Irrigation	mm	In the MIRCA 2000 database (Portmann, Siebert and Döll, 2010) do distinguish between areas rainfed and irrigated per crop. For the irrigated crops, this dataset is leading. For the other crops, (Monfreda, Ramankutty and Foley, 2008) data is used.	(Monfreda et al., 2008; Portmann et al., 2010)
	Irrigation management		No cell-based crop-specific data is available yet, so a default irrigation file is used. The technique is set on surface irrigation	(Aquastat, 2015)

			which wets the full soil surface, because this is the most prevalent technique according to Aquastat.	
Hydrology	Precipitation	mm	Dataset covers the period from 1958-2010. Spatial resolution is 30 x 30 arc minutes, but the values are assigned to each of the 36 enclosed 5 x 5 arc minutes grid cells.	CRU TS3.21 (Jones et al., 2012; CRU, 2013)
	Reference Evapotranspiration	mm	Daily values derived from CRU TS3.21 file of ET0	CRU TS3.21 (Jones et al., 2012; CRU, 2013)
	Curve number (CN); Readily evaporable water (REW); capillary rise parameters	mm	These are based on the volumetric water content at saturation, the field capacity, wilting point and Ksat	AquaCrop Reference Manual (Raes et al., 2018)
	Volumetric water content at saturation; field capacity (-33 kPa, pF = 2.5); wilting point (-1500 kPa, pF = 4.3); and Ksat (saturated hydraulic conductivity)	kPa	For both layers (top soil and subsoil)	(De Lannoy et al., 2014)
	Ground water table	m	Groundwater presence may influence the soil water balance due to capillary rise. In the Aqua21 model a constant water table depth throughout the growing season and over the years is used.	(Fan et al., 2013)

Appendix H: Model processes

H.1: Crop evapotranspiration (ET_c)

The evapotranspiration of a certain crop at a certain stage can be calculated in various ways. Aqua21 and Delft-Agri have different methods to calculate this value.

Aqua21

In Aqua21 the calculation of ET_c is separated into the calculation of (i) soil evaporation (E) and (ii) crop transpiration (Tr):

$$ETc = E + Tr \tag{9}$$

The soil evaporation is dependent on weather parameters; when it is hot and dry a lot of water can be lost by evaporation. It is also dependent on the canopy cover; at the beginning the soil is not covered with canopy and soil evaporation is high. Lastly, it is dependent on environmental factors such as soil water content; if there is no water in the soil, soil evaporation is hardly possible (FAO, 2016a).

The crop transpiration is calculated as follows:

$$Tr = Ks * Kstr * (Kctr * CC) * ET0 \tag{10}$$

Wherein K_s is a water stress coefficient and K_{str} a cold stress coefficient. What should be noticed here is that the crop transpiration coefficient is proportional to the canopy cover (CC), which is a distinction from the equation used in Delft-Agri. The proportional factor (K_{ctr}) is adjusted for ageing and senescence effects by CC. ET_0 is the reference evapotranspiration as in the equation above (Raes et al., 2018).

Delft-Agri

The crop evapotranspiration is calculated with one equation:

$$ETc = Kc * ET0 \tag{11}$$

Wherein K_c is the crop coefficient, which varies per growing stage and crop. In between the stages K_c is linearly interpolated. ET_0 is the reference grass evapotranspiration as determined by the FAO Penman-Monteith equation. In this study the ERA5 dataset has been used as input for ET_0.

H.2: Soil

Another difference between the two models is the way in which processes in the soil are described and handled. The soil is of high importance for both models, because herein crops grow their roots with which they absorb water.

Aqua21

A schematic representation of the soil as modelled in Aqua21 is depicted in Figure 33. The root zone can be considered as a reservoir, with incoming (irrigation, rainfall and capillary rise) and outgoing (evapotranspiration, deep percolation and runoff) fluxes. In contrary to Delft-Agri, here capillary rise is taken into account. With the help of a soil water balance, the values for the amount of water retained in the root zone (Wr) and the root zone depletion (Dr) can be calculated and so the total available soil water (TAW) can be determined at any moment (Raes et al., 2018).

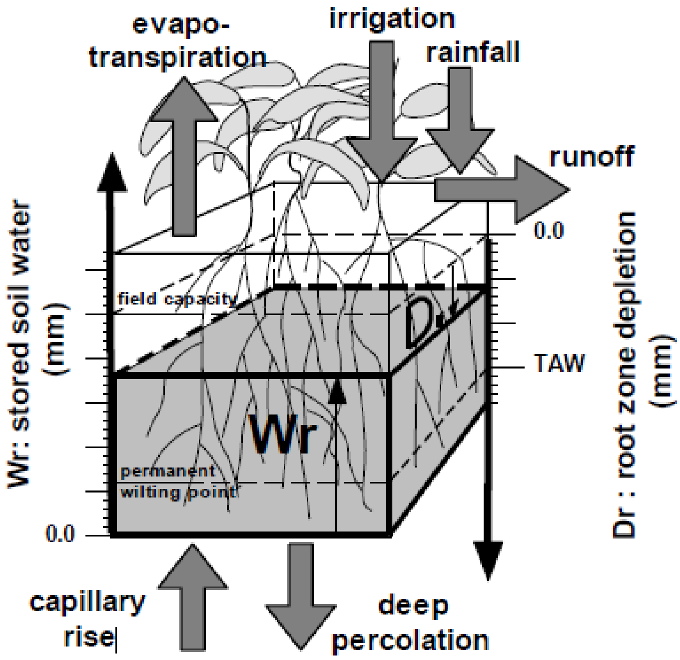

Figure 33: The root zone with indication of the in- and outgoing fluxes affecting the water stored in the root zone (Wr) and the root zone depletion (Dr) (Raes et al., 2018)

Figure 34 shows the drainage function as used in Aqua21. The use of the function is twofold: it simulates the drainage inside of the layer and the percolation out of the layer, furthermore it simulates infiltration of rainfall and irrigation. The function uses the factor tau, which is proportional to K_{sat}. It expresses the decline in soil water content from the first day of free drainage. The water content between saturation and field capacity can be drained and therefore the decline is expressed in this range (Raes, 2017).

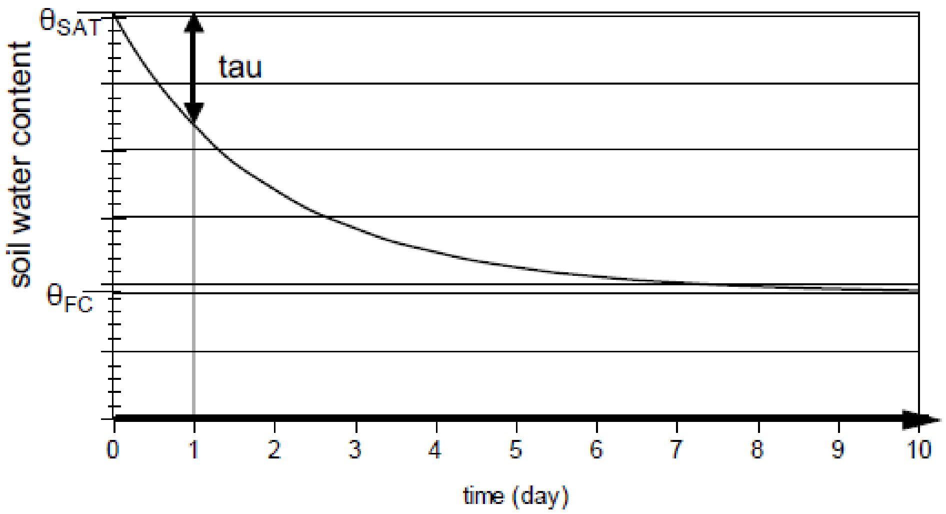

Figure 34: Drainage function describing the decline in soil water content between saturation and field capacity over time (Raes, 2017)

Figure 35 shows the various degrees of the water stress coefficient K_s. The total available water lies between the upper threshold (field capacity) and the lower threshold (permanent wilting point). As the soil moisture drops in the direction of the permanent wilting point, water stress increases and the K_s value goes to 0.

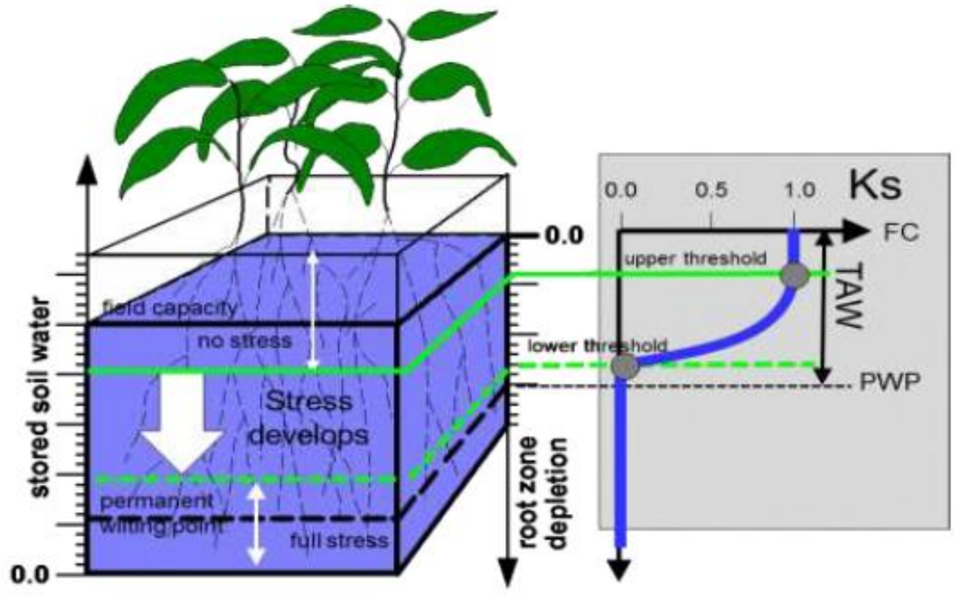

Figure 35: The Ks curve for various degrees in the root zone. The Ks value lies between an upper threshold (field capacity) and a lower threshold (permanent wilting point). In between those, the total available water (TAW) is depicted (Raes *et al.*, 2018)

Delft-Agri

In a schematic way, the soil can be seen as a reservoir, see Figure 36. It can be seen that the available moisture can be characterized by a water balance and a number of variables. Each time step, rainfall and irrigation water supply replenish the soil moisture, evaporation, drainage and seepage/percolation deplete the soil moisture. The hydraulics of water movement in the root zone are not considered, this implies that in case capillary rise occurs this is not represented in the model (Van der Krogt, 2008).

Variables that are used in the model are soil wilting point, soil field- and soil saturation capacity. Soil wilting point is the depth from which the plant cannot effectively obtain water. Soil field capacity is the depth of water held in the soil after excess water has drained away and the rate of downward movement has decreased; usually after 1 to 3 days after irrigation or rain. In the model, the field capacity is used as the target soil moisture for dry land crops. Soil saturation capacity is the level of water content at which the soil is saturated and all pores are filled with water, then the field water layer begins (Van der Krogt, 2008).

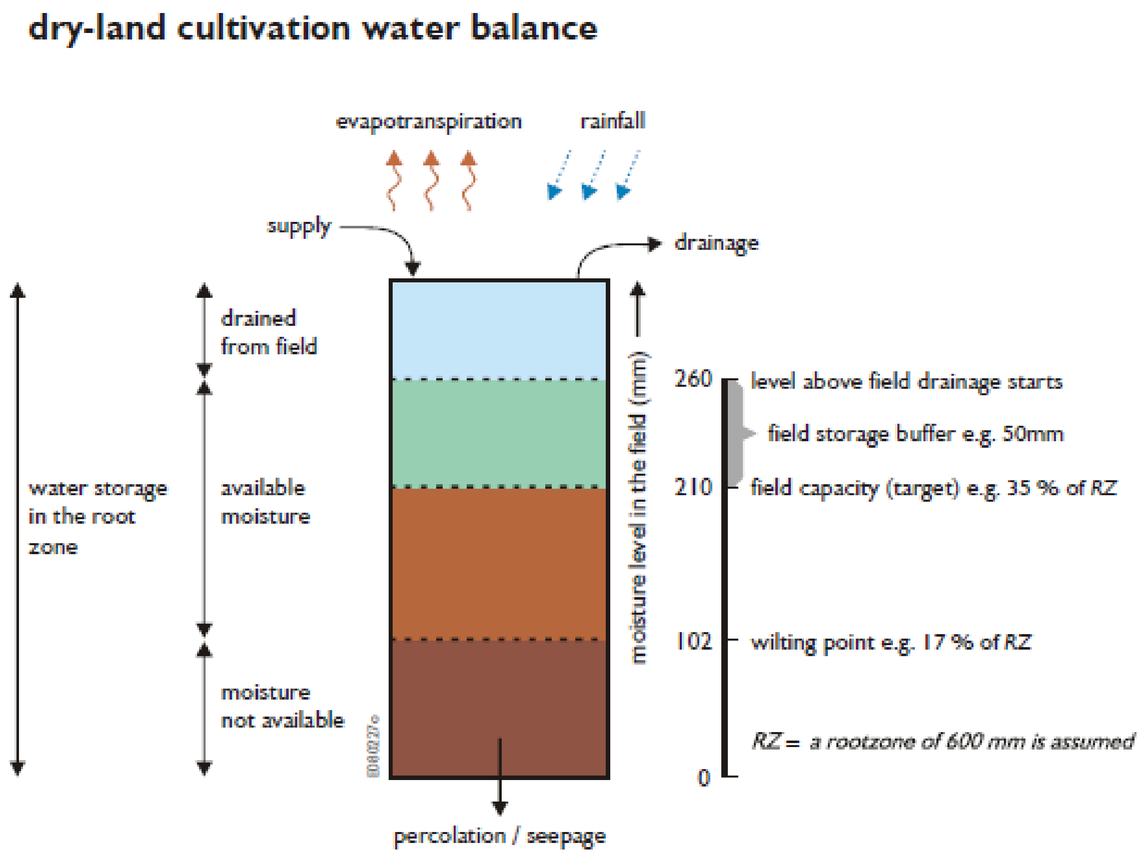

Figure 36: Schematization of field moisture for dry-land crops like potatoes ((Van der Krogt, 2008)

Now as it has become clear how the schematization of the soil is done in Delft-Agri, the computations for the gross irrigation water demand will be given, these look like equation (1), but here the gross demand (instead of the net demand) is shown including its details:

$$Dgross = \{(Psat + Fc * Evp + P) - Re\} * \frac{100}{OvAIEf} \quad (12)$$

$$Re = Rdep * \frac{Reff}{100} \quad (13)$$

$$OvAIEf = Ecv * Enr * Efa/\ 10000 \tag{14}$$

With D_{gross} the gross irrigation water requirements, P_{sat} the pre-saturation requirement, F_c the crop factor (this is equal to K_c), Evp the reference crop evapotranspiration, P the percolation, Re the effective rainfall, R_{dep} the dependable rainfall, R_{eff} the rainfall effectiveness (depending on the water supply to the area and the actual moisture on the field), OvAIEf the overall irrigation efficiency, E_{cv} the surface water conveyance efficiency which is the efficiency of the main canals in the system, E_{nr} the normal period irrigation efficiency which is the efficiency in the smaller canals managed by the farmers, E_{fa} the field application efficiency which is the efficiency that depends on the type of irrigation. The efficiencies have to be multiplied in order to know the efficiency over the whole distribution system (E-mail correspondence with Van der Krogt, January 2, 2021). In Delft-Agri the efficiencies are set at 80% (in dry conditions this can go up to 90%), this means that 80% of the water will become effectively available to the plants and 20% will be lost to evaporation and seepage and to inefficient operation in the distribution system.

From the equation it becomes clear that the water demand of the crop is taken into account by using the crop factor F_c or K_c and multiplying it with the reference Evp, however F_c / K_c is determined per crop per climatic region, but it does not take into account limitations (for example drought or senescence) during the growth period and so change in crop water requirement is not taken into account in the model. Only when the soil moisture drops below the wilting point, drought damage occurs and the plant dies.

H.3: Yield formation

Calculation methods for yields are of large importance in this research, as the yields form the output on which the model performance is tested. Delft-Agri and Aqua21 both use different methods, which are described here.

Aqua21

In Aqua21 the method of AquaCrop is used to calculate the final crop yield. It follows the equation:

$$Y = HI * B \tag{15}$$

In which Y is the Yield (tonne/ha), HI the Harvest Index (which expresses the mass of the harvested products as a percentage of the total above-ground biomass (B))(Raes, 2017). The factors HI and B capture the effects of stresses, HI for example is calculated by multiplying a factor to the reference Harvest Index (HI_0). And also the calculation of B goes back to first determining the canopy cover of the plant. Appendix C.2 shows the total equation, that consists of four steps, in more detail (Raes, 2017). What can be seen is that Aqua21 does not use the variables K_y and K_c, so for these variables, input from literature is used to use in the Delft-Agri model.

Delft-Agri

In Delft-Agri the same function for yield response is used as in CropWat, the function looks as follows:

$$\left(1-\frac{Ya}{Ym}\right) = Ky * \left(1-\frac{ETa}{ETm}\right) \quad (16)$$

In which Y_a is the actual harvested yield (tonne/ha), Y_m the maximum potential harvested yield (tonne/ha), K_y the yield response factor (which is empirically derived), ET_a the actual evapotranspiration (mm) and ET_m the maximum potential evapotranspiration (mm) (which is ET_0*K_c). This function shows that if there is a ET deficit (difference between the full potential ET of the plant with sufficient moisture supply and actual ET due to reduced soil moisture availability) the yield will be negatively influenced (linear relationship between yield and ET). In the model it is assumed that if field moisture falls below the root zone soil moisture threshold for drought stress, the crop on that field is lost (Van der Krogt, 2008). In relation to the equation, this means that actual evapotranspiration, which is a function of the remaining soil moisture, becomes less than the potential evapotranspiration (Van der Krogt, 2008).

In this study, Y_m is based on national statistics of Germany (Destatis, 2020b), an average of the period 1997-2002 has been used as this period covers the year 2000. Y_m has been determined by multiplying the corresponding national average yield values per crop by a factor of 1.2 as has been done in Mekonnen and Hoekstra (2011b). As there is no Y_m value for every year, factors that improve yields such as crop breeding and fertilization are not taken into account in the modelling scheme.

Appendix I: Definitions of water use

Water use can either refer to water withdrawals or water consumption. Water withdrawal includes water loss and returns, but water consumption excludes them. Therefore, water consumption refers to the amount of water removed from water resources and evaporated to the atmosphere (Liu et al., 2017). The majority of existing water studies related to drought focus on water withdrawal as an indicator of water use. This is done since consumption is normally smaller than withdrawal, and the ratio of consumption to average available renewable water resources then indicates an unrealistic level of drought (Liu et al., 2017). Aqua21 and Delft-Agri have different definitions of water use.

Aqua21

In relation to the phenological model Aqua21, water use refers to water consumption. The model looks into the water consumed and evapotranspirated by the crop as described by the water footprint concept (Appendix B). In the model water consumption and evapotranspiration can be attributed to its source: green and blue water (Hogeboom *et al.*, 2020). The equations for blue and green crop water use are as follows:

$$Blue\ water = eb_{cr} + eb_i + tb_{cr} + tb_i \tag{17}$$

In which eb stands for evaporation of blue water and tb for transpiration of blue water (both in mm). Cr stands for capillary rise and i for irrigation of surface and groundwater.

$$Green\ water = eg + tg \tag{18}$$

In which eg stands for evaporation of green water and tg for transpiration of green water (both in mm).

In Aqua21 the root zone can be considered as a reservoir, in which blue and green fluxes come in and go out. There is no order in the source of the incoming fluxes within the model. There is water available, regardless of its source, which is used by the crop to grow and in case of water shortage, stresses on the plant occur. This makes the model different from Delft-Agri, in which the order of the source (green or blue water) can be set.

Delft-Agri

In relation to the water demand and allocation model Delft-Agri, water use refers to water withdrawals. The model uses an efficiency parameter to set the efficiency of field application depending on the type of irrigation. In Delft-Agri the efficiencies are set at 80% (in dry conditions this can go up to 90%), this means that 80% of the water will become effectively available to the plants and 20% will be lost to evaporation and seepage and to inefficient operation in the distribution system

(Van der Krogt, 2008). The two last mentioned points; seepage (water return) and inefficient operation in the distribution system (water loss) indicate water use as water withdrawal.

However, before irrigation water is applied to the crops, the crops are fed with water from the field buffer storage and from rainfall. If there is still water demanded by the crops after that, the irrigation sources surface water is used (Van der Krogt, 2008). That means, first green water sources are used and then, if needed, blue water sources are used. However, the ratio green-blue in the total use is not determined by the model. Therefore, in order to calculate the amount of green and blue water used by the crops over the growing season, the following equation is used:

$$Blue\ water\ (needed\ irrigation\ water) = ET0 - Re - Psat \qquad (19)$$

$$Green\ water = Re + Psat \qquad (20)$$

In which ET_0 is the reference evapotranspiration of the crop (over the whole season) (mm); Re the effective Precipitation (mm) (over the whole season). P_{sat} the pre-saturation requirement (mm), this is depending on the type of soil and the moment of the season, because after the first harvest the soil water is not replenished yet and so the second harvest cannot make use of soil water.

Appendix J: Fluctuations in production over the years

Figure 37 shows the fluctuations in production (tonne) over the years of the Aqua21 model (Hogeboom et al., 2020). The production is estimated per type of crop for the five selected Bundesländer together. It can be seen that the production of sugar beet fluctuates a lot, whereas the production of oats is stable over the years. Potatoes and maize nearly have an equal amount of fluctuations.

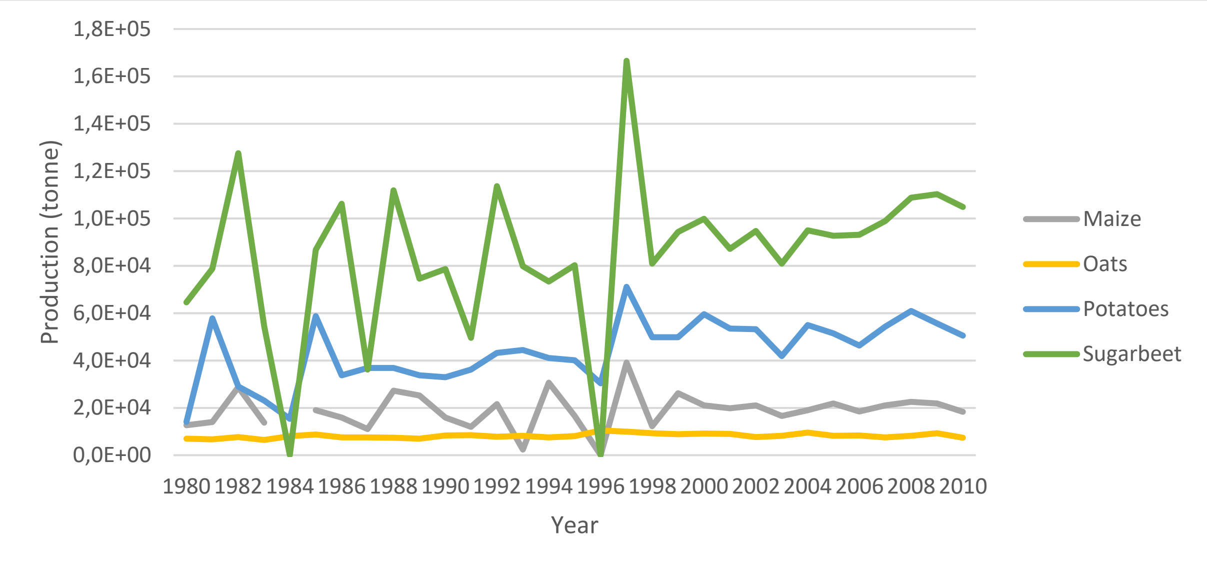

Figure 37: Production (tonne) for the selected five Bundesländer together, per type of crop, per year for the period 1980-2010. Data from the Aqua21 database (Hogeboom et al., 2020)

Appendix K: Production output (tonne) Aqua21

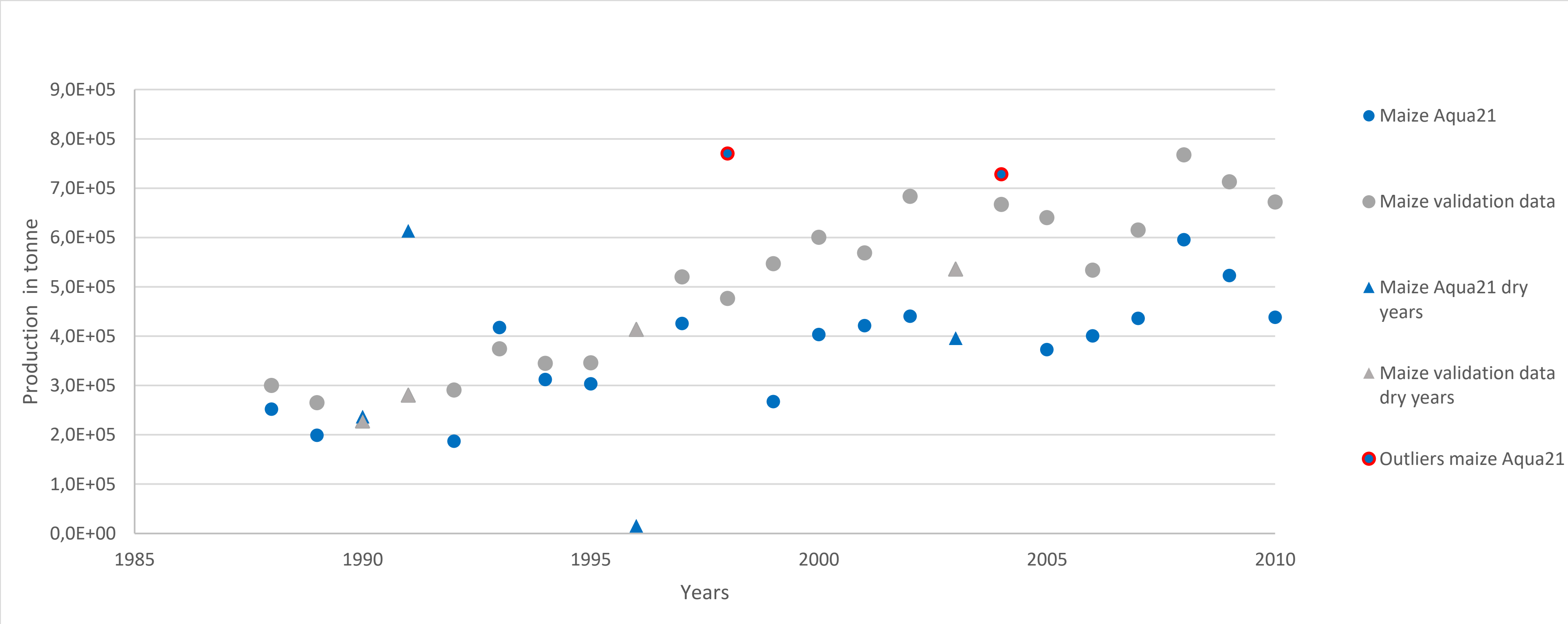

Figure 38: Performance assessment on yearly production model output of Maize (Aqua21) in tonnes for Baden-Württemberg

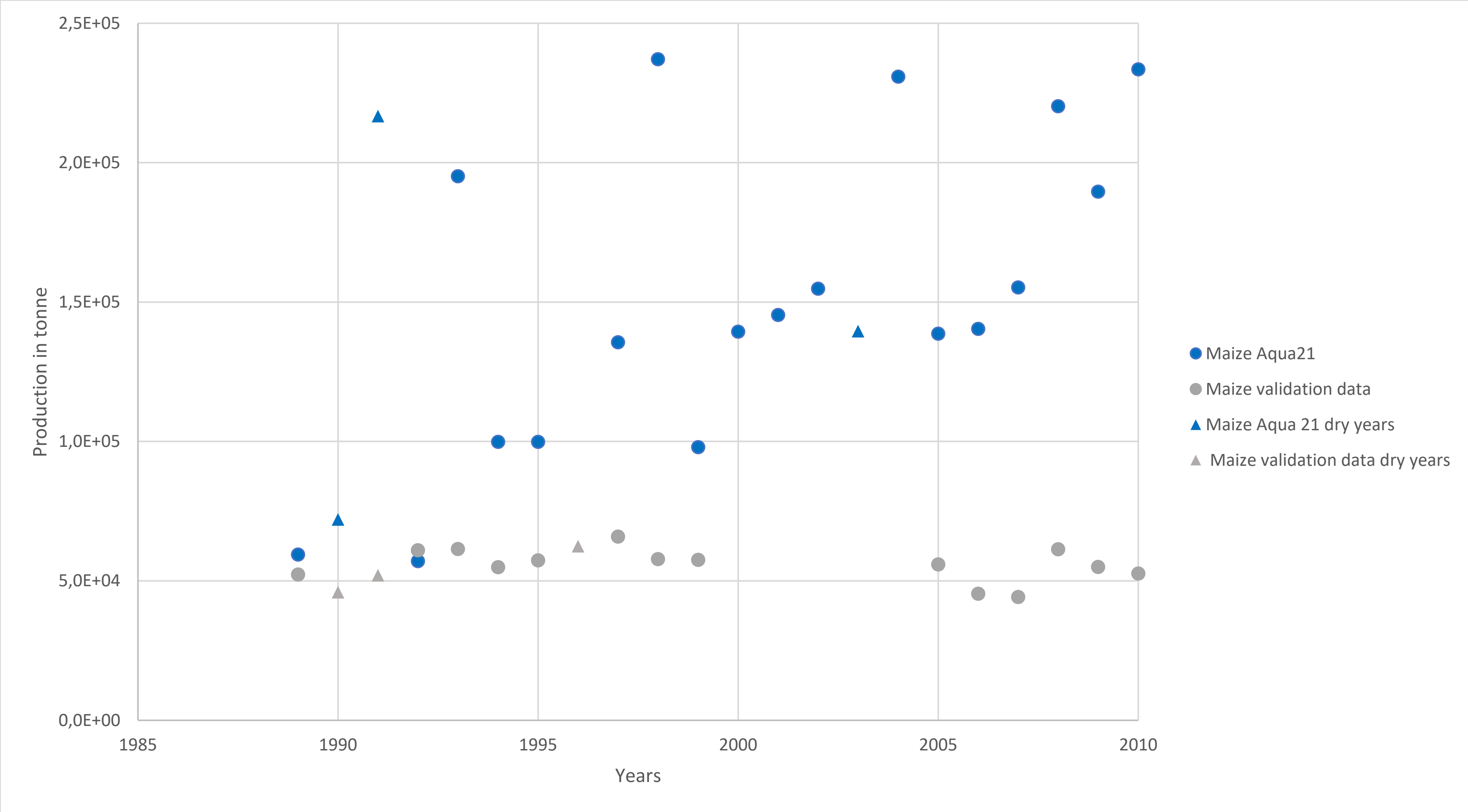

Figure 39: Performance assessment on yearly production model output of Maize (Aqua21) in tonnes for Hessen

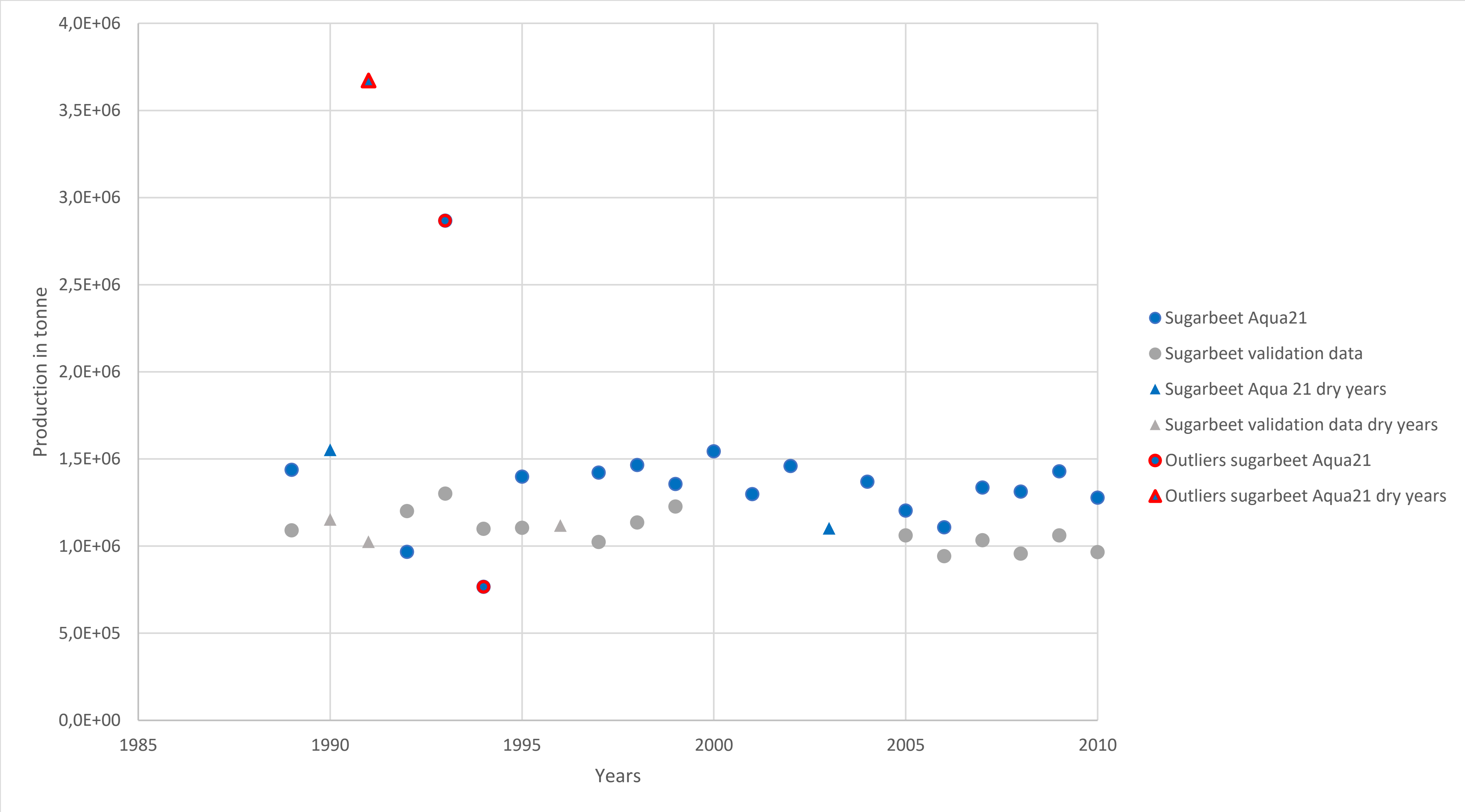

Figure 40: Performance assessment on yearly production model output of sugar beet (Aqua21) in tonnes for Hessen

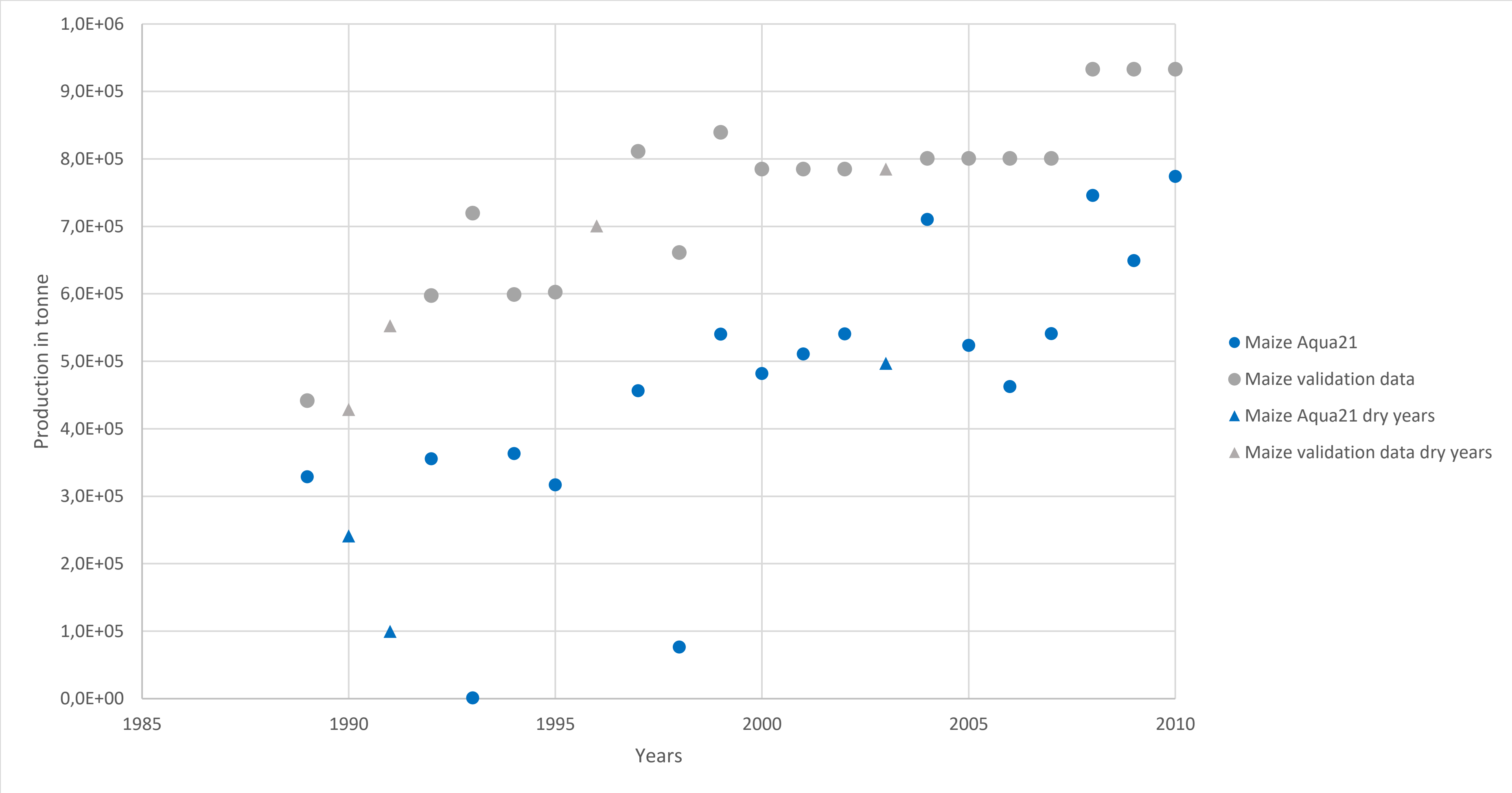

Figure 41: Performance assessment on yearly production model output of Maize (Aqua21) in tonnes for North Rhine Westphalia

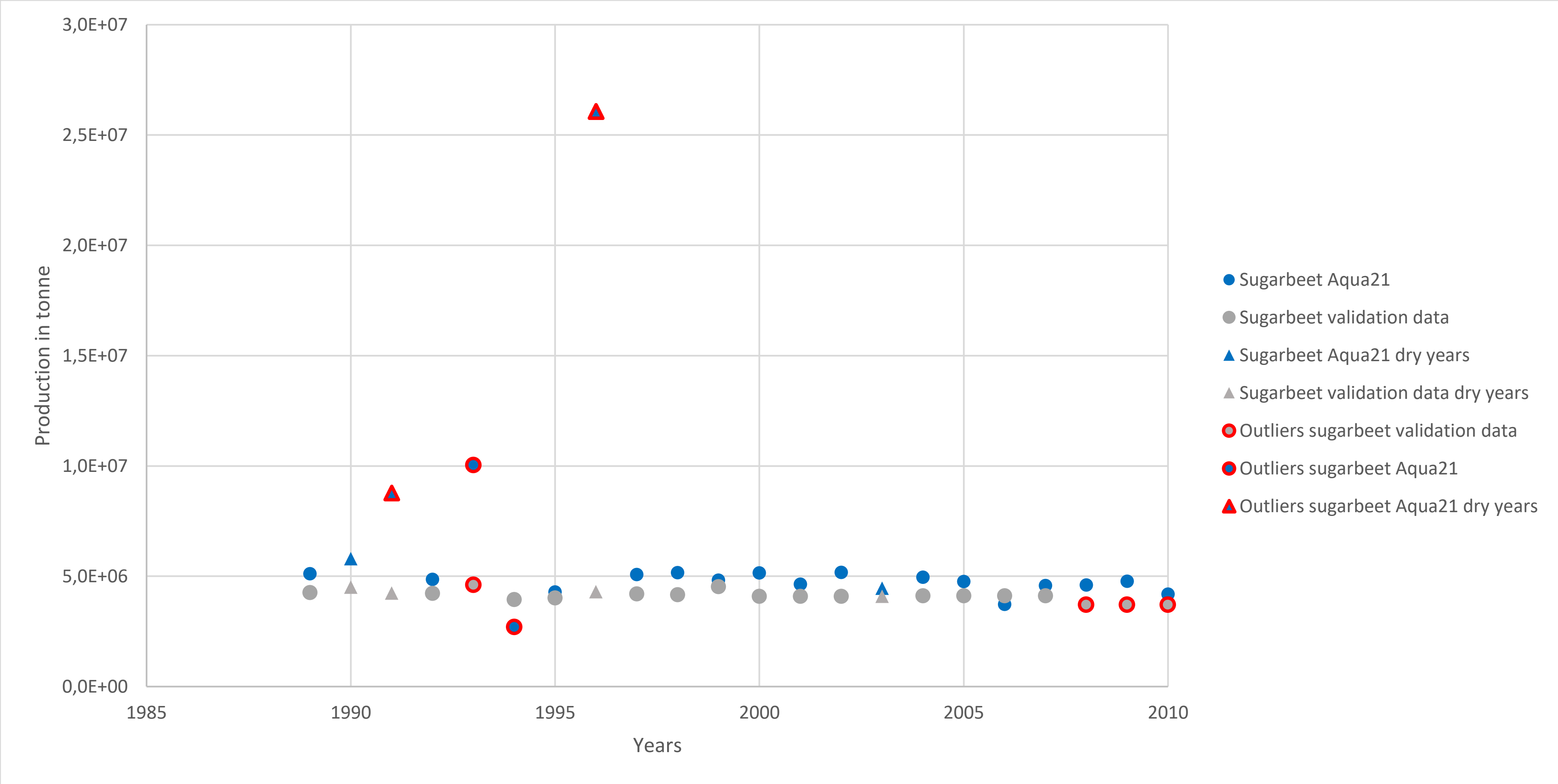

Figure 42: Performance assessment on yearly production model output of sugar beet (Aqua21) in tonnes for North Rhine Westphalia

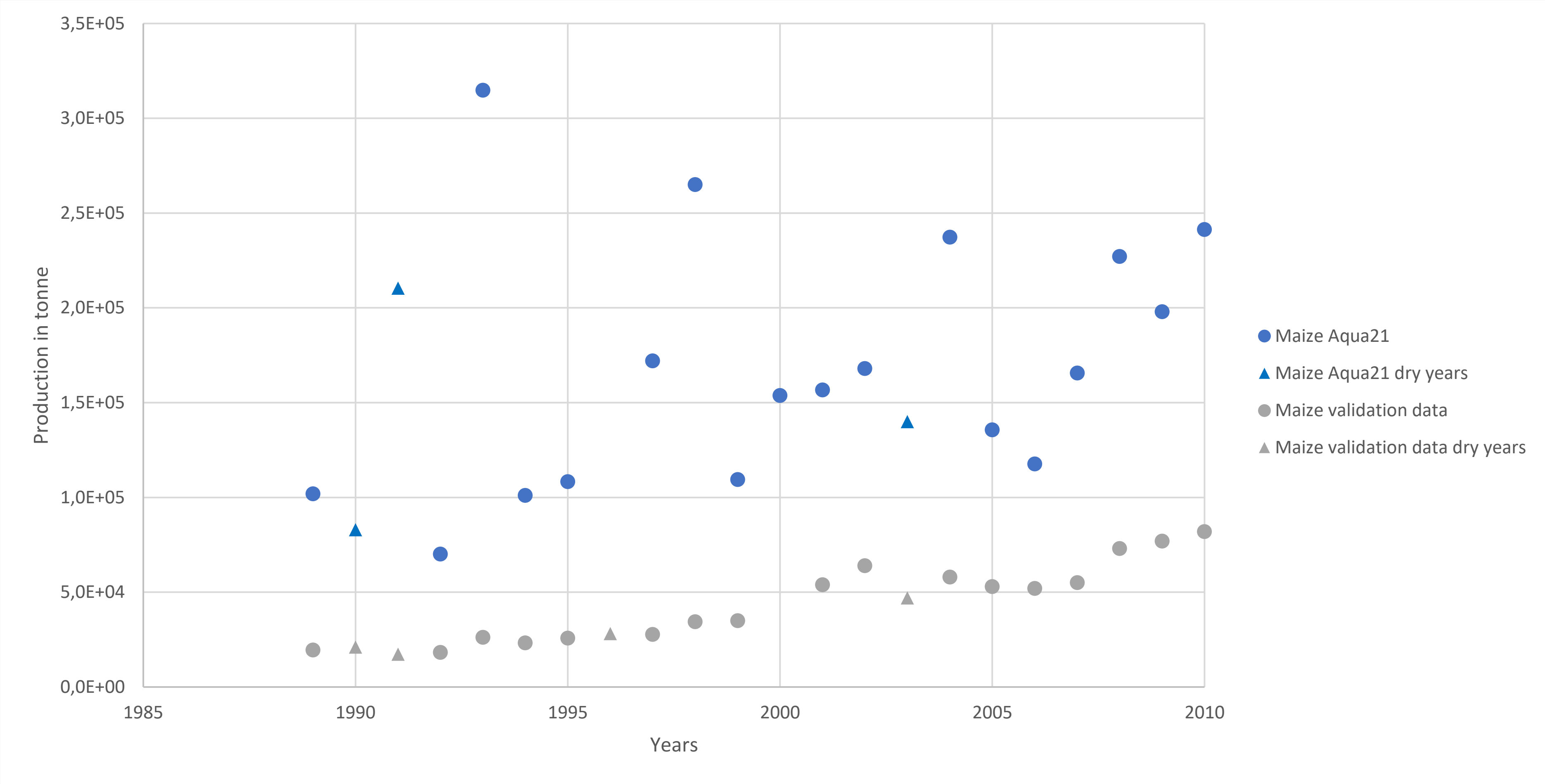

Figure 43: Performance assessment on yearly production model output of Maize (Aqua21) in tonnes for Rhineland Palatinate

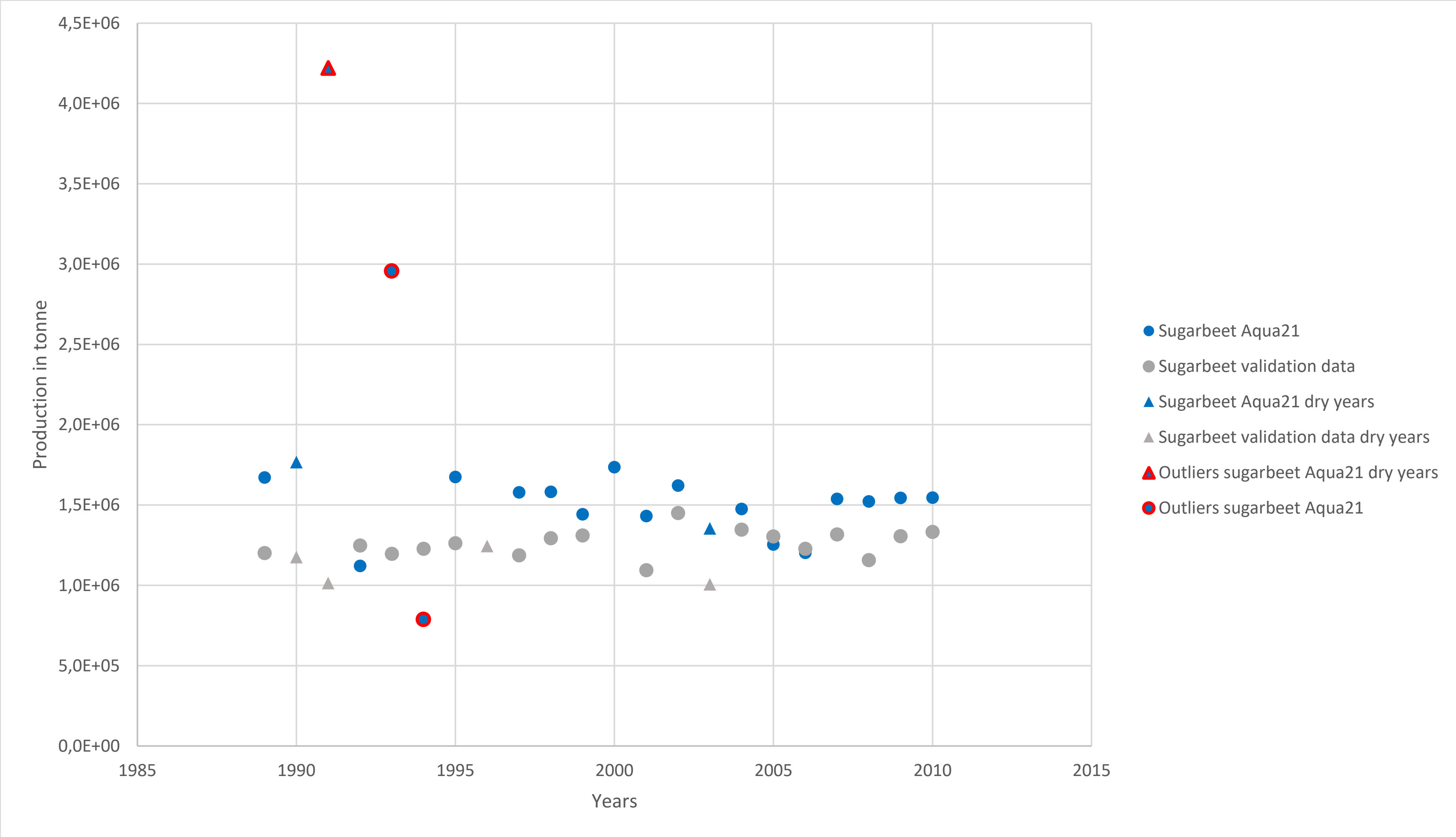

Figure 44: Performance assessment on yearly production model output of sugar beet (Aqua21) in tonnes for Rhineland Palatinate

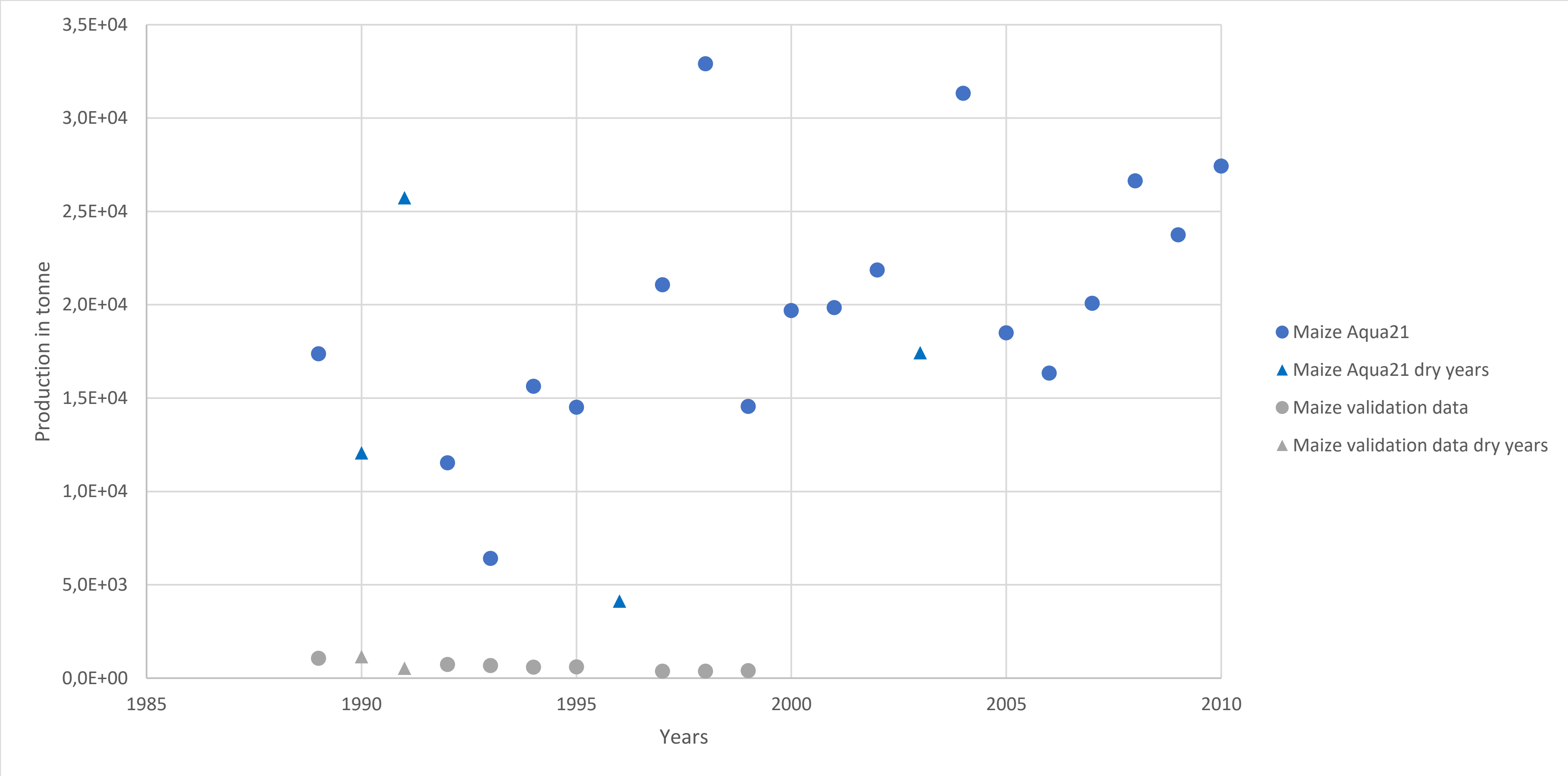

Figure 45: Performance assessment on yearly production model output of Maize (Aqua21) in tonnes for Saarland

Appendix L: Influence of scaling to national statistics

The variables production (tonne) and harvested area (ha) are further investigated in order to know if data is influenced by scaling to national statistics. Figure 46 and Figure 47 show the scaled and unscaled production of the four selected crops in this study. The production (tonne) variable turns out not to be influenced by scaling to national statistics since peaks for sugar beet and maize are seen both in the scaled as unscaled production data of Aqua21. Figure 48 and Figure 49 show the harvested area (ha) of maize and sugar beet for Germany over the years. The variable harvested area (ha) is influenced by scaling to national statistics since a small increase in harvested area for Germany can be noticed for both sugar beet and maize around the year 1991 (Hogeboom et al., 2020).

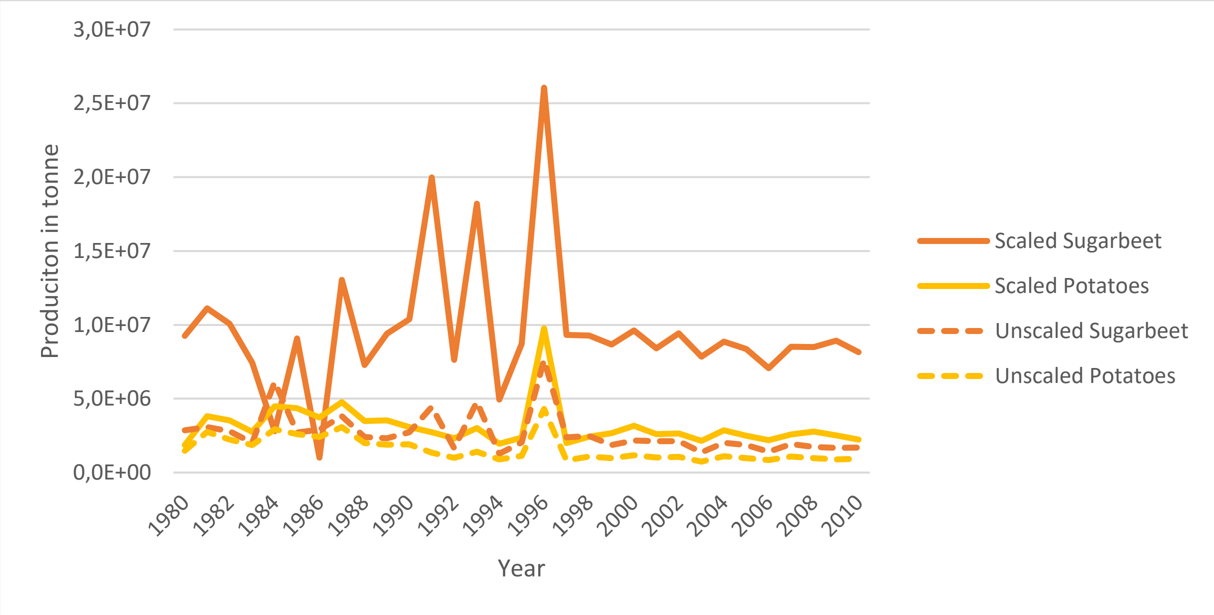

Figure 46: Scaled and unscaled production of sugar beet and potatoes in tonne per year for five Bundesländer together

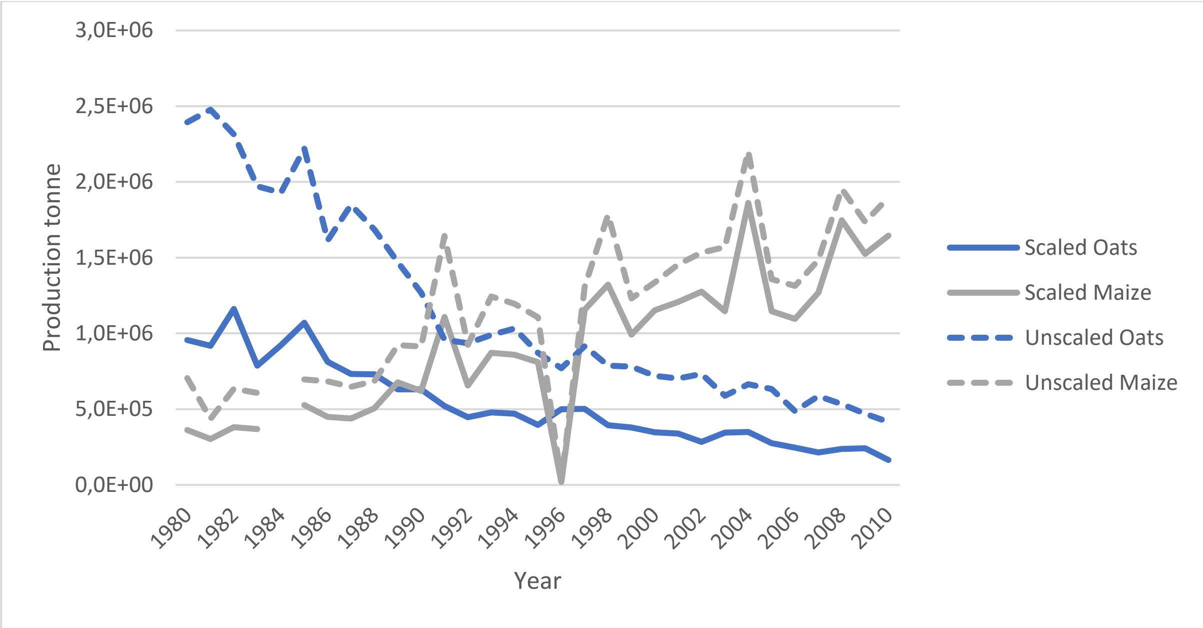

Figure 47: Scaled and unscaled production of oats and maize in tonne per year for five Bundesländer together

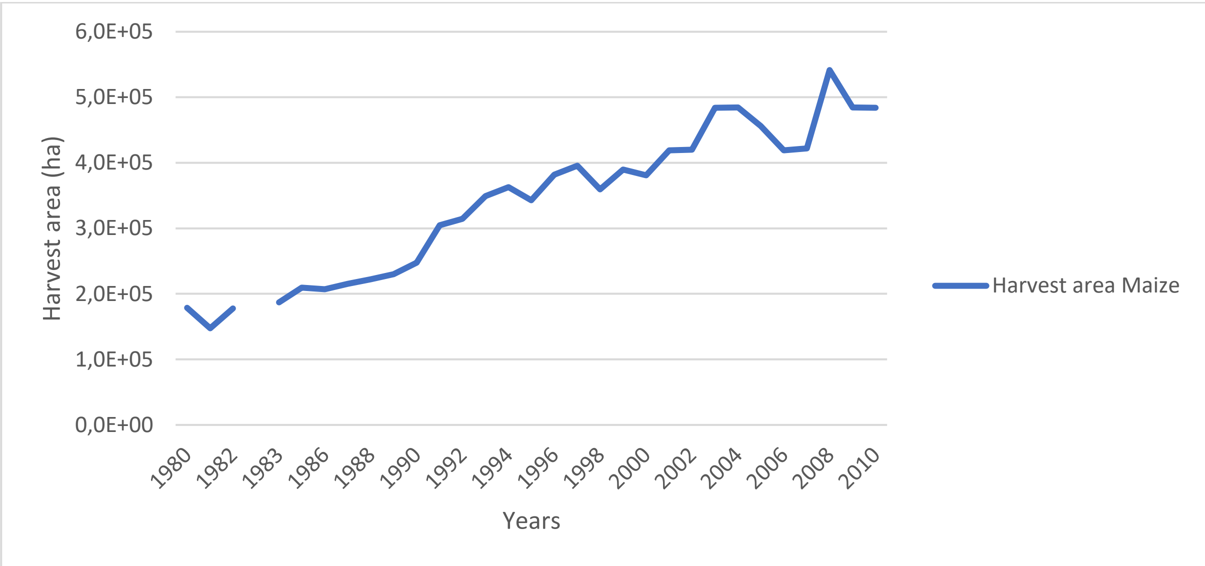

Figure 48: Harvest area (ha) of maize for Germany per year over the period 1980-2010 according to Aqua21

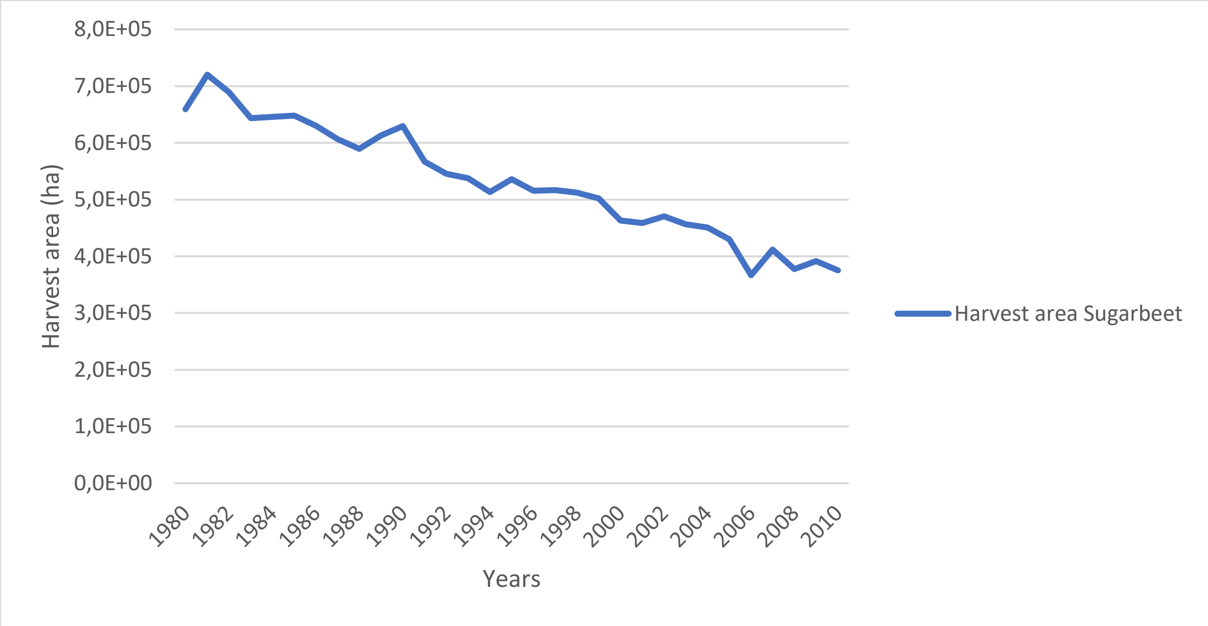

Figure 49: Harvest area (ha) of sugar beet for Germany per year over the period 1980-2010 according to Aqua21

Appendix M: Validation Delft-Agri

In this appendix, the Delft-Agri variable 'demand from the system' (m^3/s) for the various sub-basins is shown. This is the irrigation water demand from surface water under the crop plan irrigated and rainfed crops (Table 3).

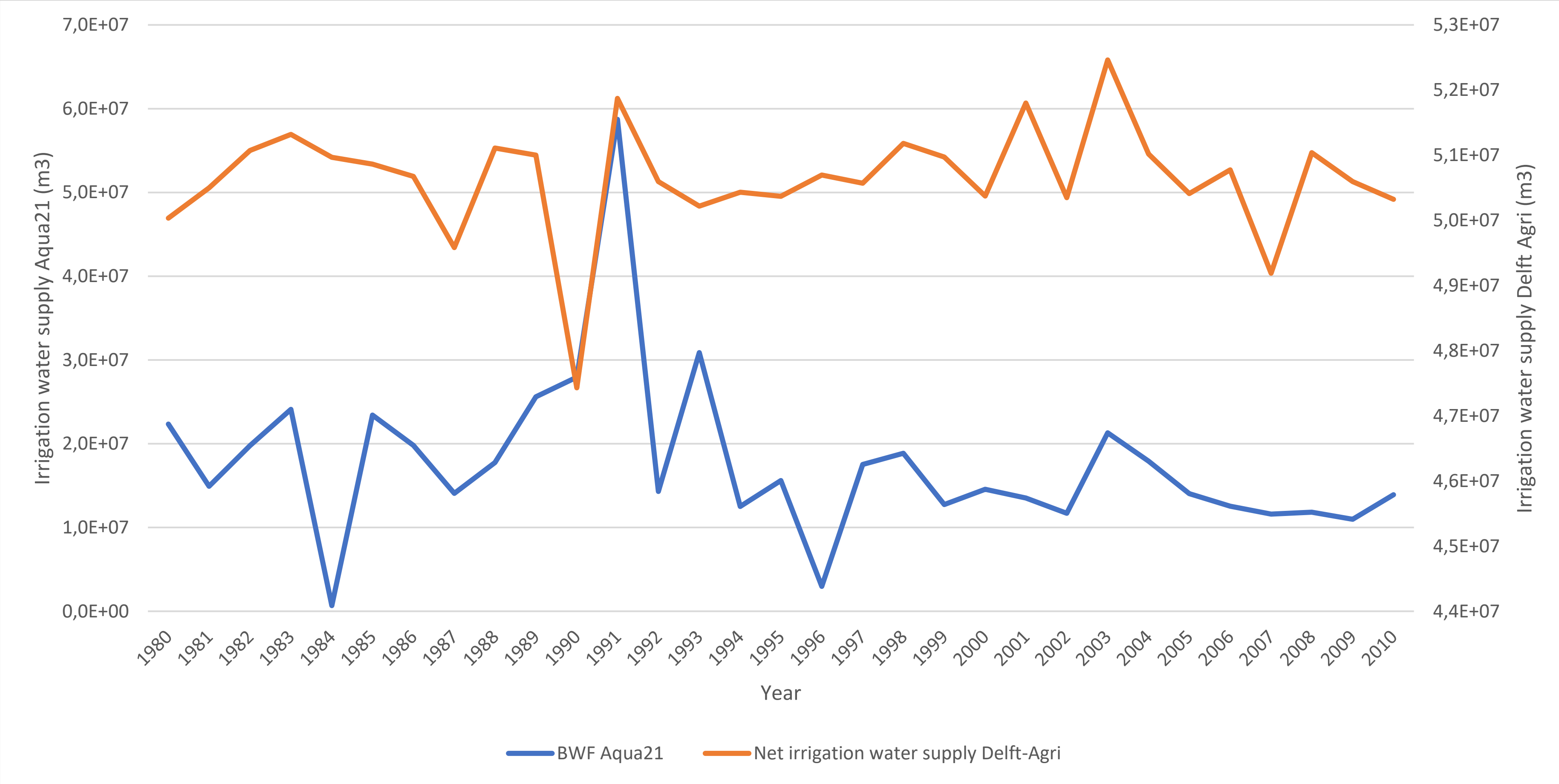

Figure 50: Yearly Blue Water Footprint (Aqua21) and Net Irrigation Water Supply (Delft-Agri) in m^3 during the growing season for the Main

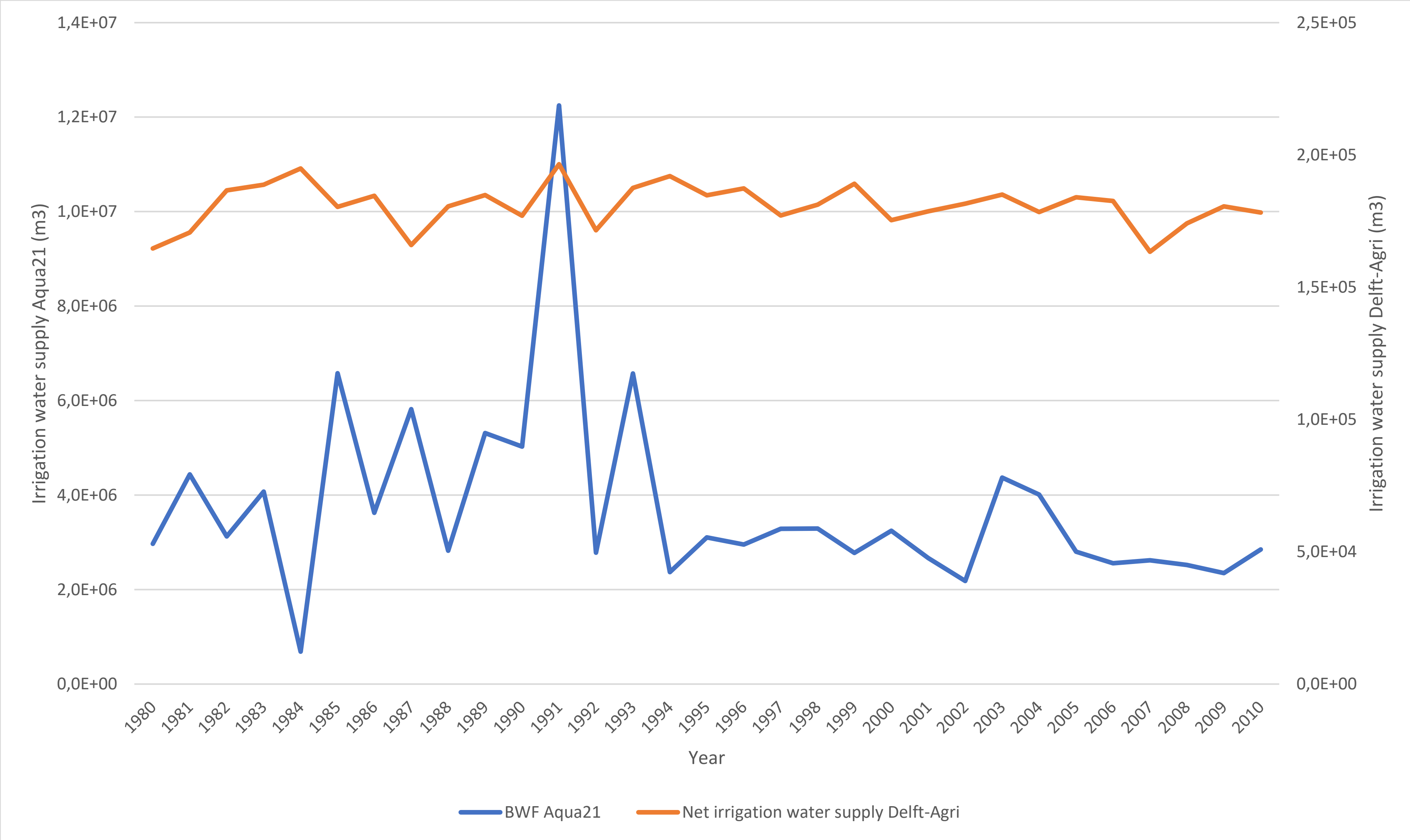

Figure 51: Yearly Blue Water Footprint (Aqua21) and Net Irrigation Water Supply (Delft-Agri) in m³ during the growing season for the Mosel/Saar

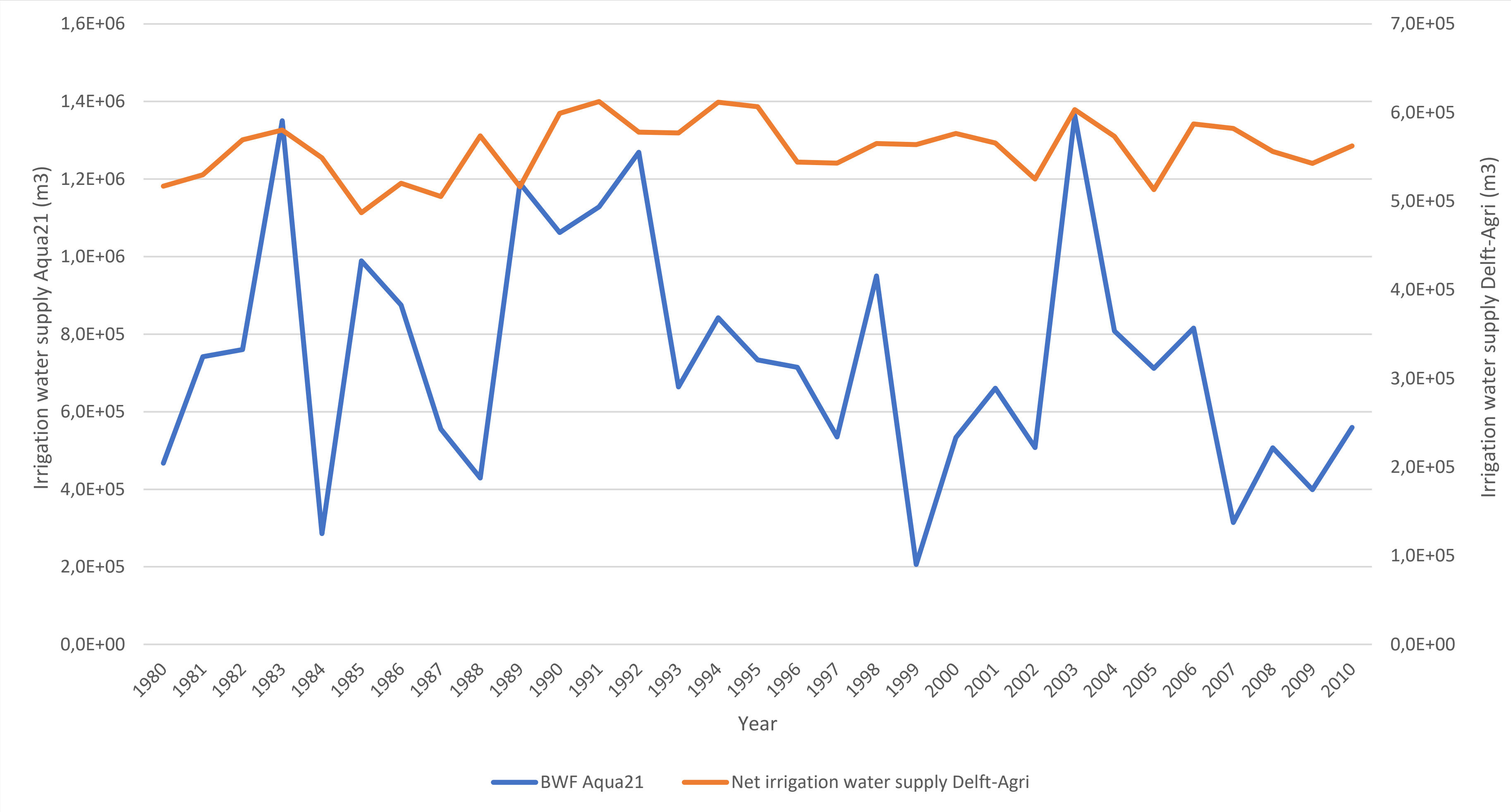

Figure 52: Yearly Blue Water Footprint (Aqua21) and Net Irrigation Water Supply (Delft-Agri) in m³ during the growing season for the Bodensee/Alpenrhein

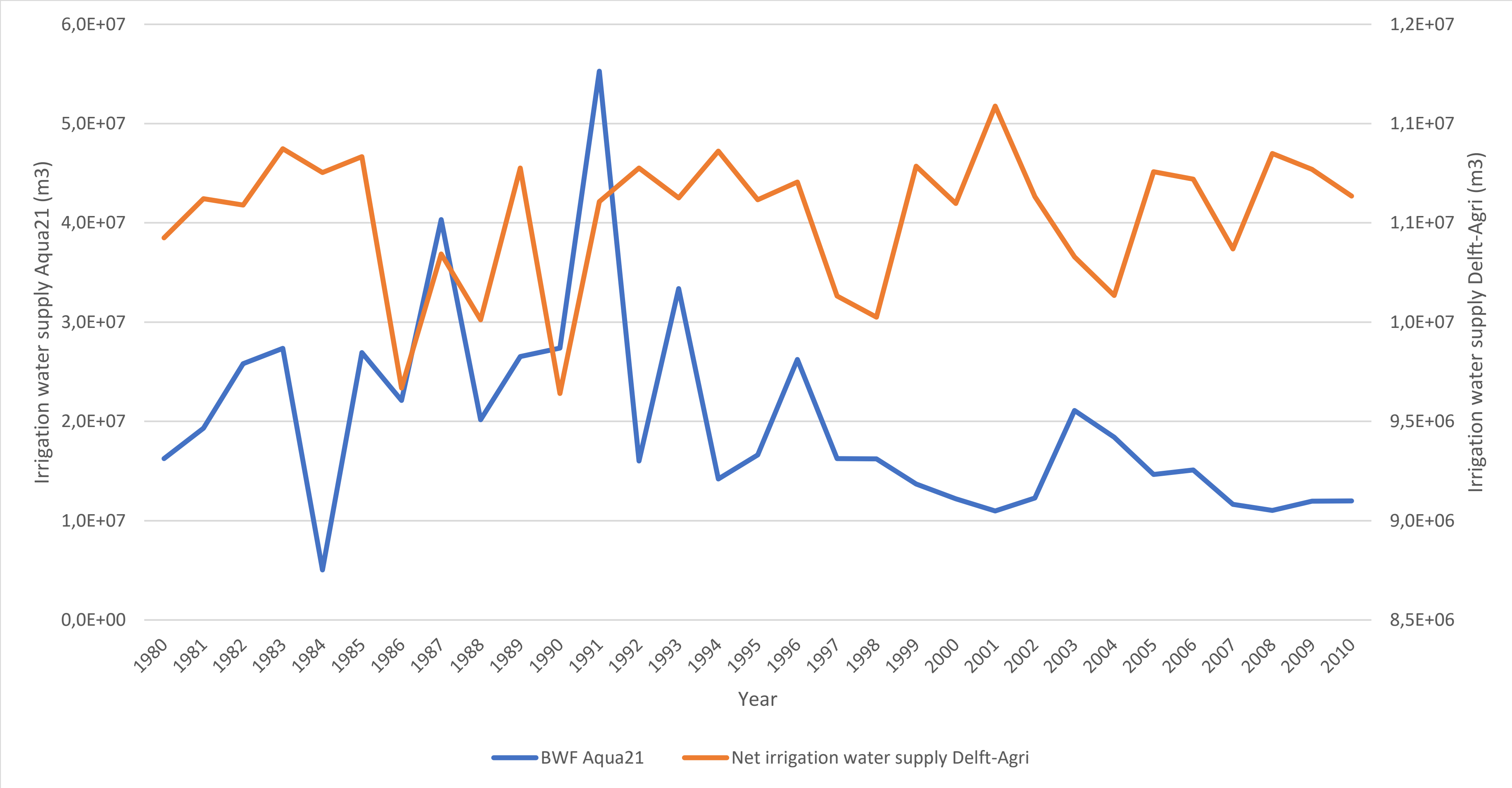

Figure 53: Yearly Blue Water Footprint (Aqua21) and Net Irrigation Water Supply (Delft-Agri) in m³ during the growing season for the Neckar

Appendix N: Irrigated and rainfed harvested areas for the Rhine basin

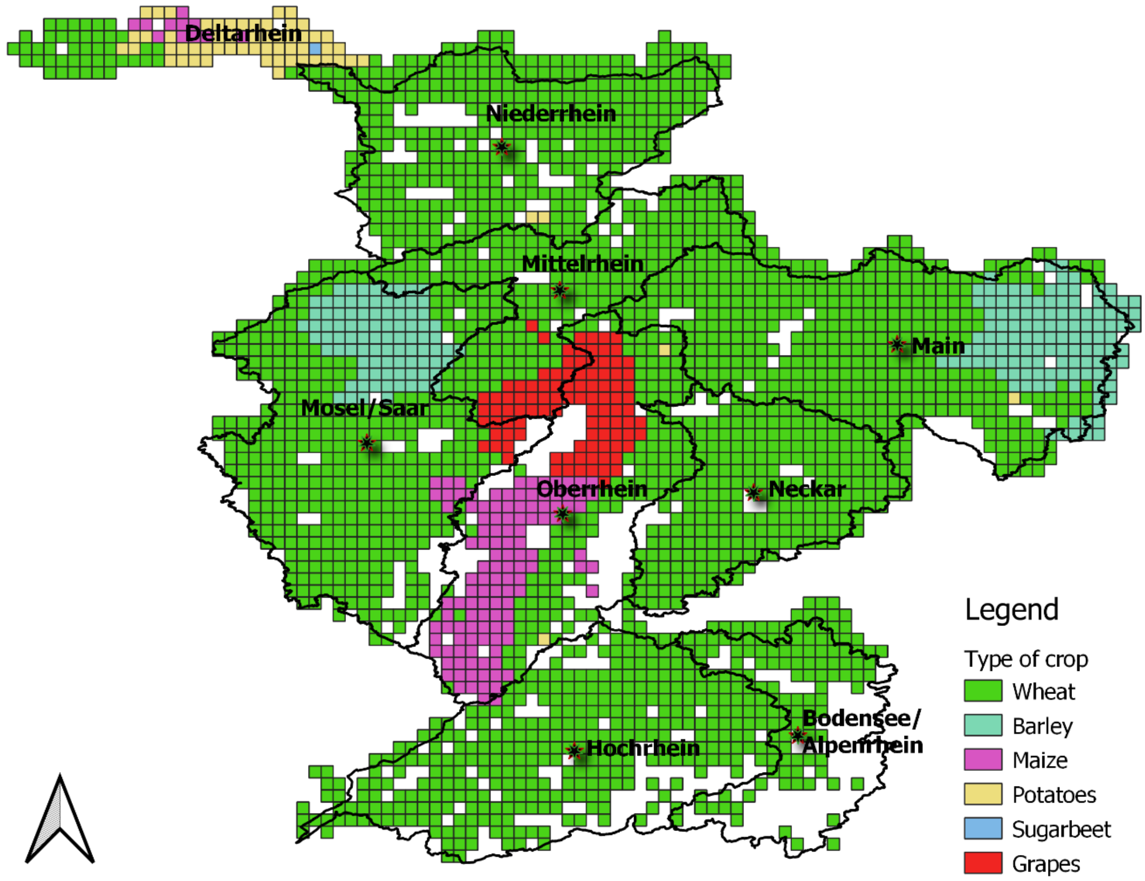

Figure 54: Schematization of the Rhine basin in 5 x 5 arc minutes by the Aqua21 model. The irrigated and rainfed harvested areas for the year 2000 for the Rhine basin are shown. Per cell, the crop with the largest irrigated and rainfed harvested area together is depicted.