Hydrological Water Balance Modelling

Determining the feasability of closing water balances of the subcatchments in the Overijsselse Vecht basin

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Preface

Before you lies my bachelor thesis, *Hydrological Water Balance Modelling: Determining the feasibility of closing water balances of the subcatchments in the Overijsselse Vecht basin*. A document where I can proudly present my findings gathered during my graduation period at the water board Vechtstromen.

I am very pleased that I was able to combine two of my main interests in the civil engineering field, Water Management and Hydrological Modelling, and apply them in a graduation project. The practical approach involved in this type of subject, which is largely based on fundamental theories of hydrology, ensured that at no point did I look up to my graduation assignment.
I had the opportunity to do my own field research when I got stuck with my research. This resulted in a small photo report that I was able to use in my thesis to explain some things if necessary, and gave me many practical insights about the project area.

First of all, I would like to thank Han Su for the great guidance at UT. I only had to send him an e-mail if I couldn't figure something out and often I would quickly find myself in the social corner in the Westhorst talking to him about my thesis. Based on his good feedback, I was always able to progress further in my research. I really appreciated all this.
I would also like to thank Jeroen van der Scheer for all the help I received for the assignment from Waterschap Vechtstromen. With the help of his expertise, I was able to achieve a lot and learn many new things. With this, I would also like to thank a colleague of Jeroen's, also an acquaintance of mine, namely Sjon Monincx. Sjon helped me find a graduation project at Waterschap Vechtstromen. I would also like to thank all other colleagues of Joeren and Sjon for their expertise, feedback and friendliness in the office.
Last but not least, I would like to thank my parents. They always supported me during my bachelor, even to the extend that on may 28th, we went on a field trip together by bicycle in the project area to gather information and take photographs.

Wybren de Jong

Summary

This research was commissioned by Water Board Vechtstromen to better understand the hydrological processes at play in their management area. This was done primarily to gain more insights into what is going on in the area, explore potential risks and uncertainties, and provide an informative basis for the water board's future plans for expanding their measuring network. This was achieved by setting up a hydrological water balance model in the python programming language, which can generate water balances and other forms of output based on data on hydrological processes such as discharge, precipitation and evaporation.

The research took place in three phases, an orienting phase, a design/programming phase and an output/presentation phase.
By gathering data on the area, and input from the water board in the orienting phase , requirements could be established that the model should meet. It also identified some uncertainties and issues that were highlighted later in the study.
During the design phase, a theoretical framework was established. These theories were applied in the model. Also, in addition to the hydrological processes, some other functions were incorporated into the model such as an import function for data, multiple output functions, and the ability to generate other statistics of interest to the water board in addition to water balances.
A field study was also conducted due to a gap in knowledge. By visiting the project area, an inventory was made of possible problems that may exist in the area.
This research has three types of outputs. The hydrological model is an output, and can be used for any other studies within the Vechtstromen Water Board. Calibrated and uncalibrated water balances were produced that provide an insight into the hydrological processes and uncertainties at play in the area. Third, some interesting side output has been generated. An unrealised measuring station has been modelled and a theoretical seepage investigation has been done.

From the research output can be concluded that it is feasible to set up water balances for these type of areas, but it is difficult to calibrate and validate the data from it. Based on the calibrated data, it is concluded that one of the biggest uncertainties is that most of the measuring points (could) provide structurally incorrect data. Therefor, the main recommendation for the water board is to re-calibrate their measuring points before further investigation into water balances is done.

Keywords: Water Balance, Hydrological Modelling, Model Development.

Figure 1: Waterway intersection at De Haandrik (Photograph taken by author on 28-5-2023)

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Acronyms

API	Application Programming Interface.
CSV	Comma-Separated Values.
GUI	Graphical User Interface.
MP	Measuring Point.
PNG	Portable Network Graphics.
REST	Representational State Transfer.
RWS	Rijkswaterstaat.
RWZI	RioolWater ZuiveringsInstallatie, Dutch traslation of STP.
SPEI	Standardized Precipitation-Evapotranspiration Index.
SQL	Structured Query Language.
STOWA	Stichting Toegepast Onderzoek Waterbeheer.
STP	Sewage Treatment Plant.
UMP	Unrealised Measuring Point.

1 Introduction

1.1 Problem context

Water seems like something natural. We turn on the tap, and clean and fresh water comes out, any time of the day. However, in recent years, more and more problems have surfaced regarding water. Due to a rise in the global average temperature, droughts and extreme precipitation events are becoming more frequent. One of the main results of this is that the availability of drinking water may not be as reliable in the future as we are used to now (IPCC, 2022), but also trends in extreme precipitation events can be clearly distinguished (Eden et al., 2018).

Recently, an example of a heavy weather event stressed the fact that extreme weather events heavily impact the environment, but also a knowledge gap is present within water related governmental institutes. The heavy rainfall floods in Limburg of 13 july 2021 were a wake-up call for water related institutes in the Netherlands. Heavy rain struck the region, not necessary unusual, but this rain persisted for days. Add to this that areas around Limburg also received a lot of precipitation, resulting in high water. This resulted in severe inconvenience and heavy damage in the region. On the 11th of march 2022, an advisory letter was presented at the House of Representatives. The document insisted that the quality of monitoring and prediction of precipitation and (river)discharge should be improved. One of the key messages was also that understanding the *current* situation can help us predict and adaptively respond to possible *future* situations (Harbers, 2022). It can be concluded that the Netherlands is close to a water management paradigm shift.

The water board Vechtstromen is currently looking into extending the network of measuring devices in their operational area. This means that a lot of additional data will be gathered to get a better view on the hydrological processes in their area.
Another way a waterboard can gather an better understanding of the hydrological processes preset in an area, is by setting up water balances. A water balance is a fundamental concept in hydrology that describes the relationship between the input and output of water in a particular region (Sutcliffe, 2004). By accounting for all water inputs, outputs, and changes in storage, water balances could serve as a vital tool for water boards to assess the availability and demand of water resources, make informed decisions, and plan for the future. By setting up water balances, it is possible to better understand the impacts of climate change on the water cycle and identify areas that are particularly vulnerable to extreme weather events (European Commission, 2015).

However, before such weaknesses can be identified, closing water balances will have to be established. Therefor, the Vechtstromen water board has requested for research into the possibilities of preparing water balances. This research focuses on two things. The preparation of a water balance model in the python programming language, and the application of the developed model to an existing area. These two goals are very much intertwined, because certain requirements a model must have are based on properties of an area. This is further explained in the method, section 4.

1.2 Research gap

The Vechtstromen water board does not have a good picture of the state of water balances in the subareas of their managerial area. Since the waterboard will be placing more measuring devices, it is important to have an better insight in how the current situation is, and check if these measuring stations fall in line of what was expected by water balances. The water board does not have a model in which water balances can be set up, and would like to have a tool which fits their needs. The understanding of water balances in the operational area of the water board can help with decisions and finding potential weaknesses in the system regarding to water management.

1.3 Research aim

The purpose of this research is to determine how feasable it is to set up water balances in the managerial area of the water board Vechtstromen. This is done by programming an applied water balance model for subarea's in the managerial area in programming language python, which can calculate water balances for the water board. By gathering precipitation-, evaporation-, discharge-data, and and other forms of water flows, the water balance can be set up in the model. This output water balances will be evaluated and conclusions will be drawn from these outcomes. The resulting calibrated model can be used by the Vechtstromen Water Board to monitor and validate their current measuring points, and get a better insight into the hydrological processes in the area.

1.4 Research questions

Three research questions were established to further shape the research and development of a water balance model. Some of these questions in turn have sub-questions, which define the scope of the main question.

1. Which features and processes are incorporated into the developed water balance model?
   This research question addresses one of the final results of the study, namely the functions of the water balance model.

2. To which extend can the water balance be closed with the developed water balance model?
   This research question with its sub-questions adresses the results coming from the model, and is mostly focused on the performance of the model and its output.

   (a) What are the biggest hydrological processes in the area?

   (b) Which processes generate uncertaincy within the water balance?

   (c) What is the most detailed resolution in which the model still gives sufficient results?

3. How does the model support the water board in their operational water management?
   This research question addresses how the Water Board's desires are represented in the model and research, and how the water board Vechtstromen can use the resulting model for operational purposes.

1.5 Report outline

The thesis starts with a description of the study area. This sets the context for the research, providing details about the geographical location, hydrological characteristics, and relevant water management infrastructure, such as measuring stations.

The next chapter delves into the theoretical framework, covering the underlying theories that form the basis of the study. It explores the general water balance model theory and it incorporates fundamental concepts related to processes which could be relevant for this thesis

Moving forward, the methodology chapter outlines the approach used to address the research questions. It describes how different types of data were collected and utilized in creating a Python model specifically designed for calculating water balances. The methodology includes details about data, methods of data processing, model construction and parameterization.

The subsequent chapter focuses on the results of the study. It presents the developed Python model itself, showcasing its structure, characteristics, and user interface. This model, serves as the foundation for calculating the water balances.

Following the model presentation, the thesis presents the results of the water balance calculations derived from the model. Both uncalibrated model outputs as calibrated model outputs are presented here. Any miscellaneous results are presented at the "Results: Miscellaneous section", such as seepage and the determination of an unrealised measuring point.

In the subsequent chapter, the discussion section critically examines the research findings. It addresses potential inconsistencies or limitations encountered during the research. The discussion explores challenges faced in model development, data availability, or uncertainties in the results.

The results of this research are concluded in the Conclusion section, where the research questions are answered in a focused manner. This section provides a concise summary of the main findings, and reflects how the research aim is adressed in the research.

Finally, the thesis concludes with recommendations specifically tailored for the Vechtstromen Water Board.

2 Study area

In this section, information about the study area, which has been gathered during the orientation phase of this research, is discussed.

2.1 Managerial area

The water board of Vechtstromen manages an area reaching from Emmen to Haaksbergen, and is closed in between the German border and the Rijn/IJssel catchment. The area is spread over two provinces, The province of Overijssel and the province of Drenthe.
The Dinkel, the Regge and the Vecht rivers are the three main waterways in the area. Two of these rivers, the Dinkel and the Vecht both originate in Germany, Which means that water-management authorities in Germany are therefore an important partner for the Vechtstromen water board.

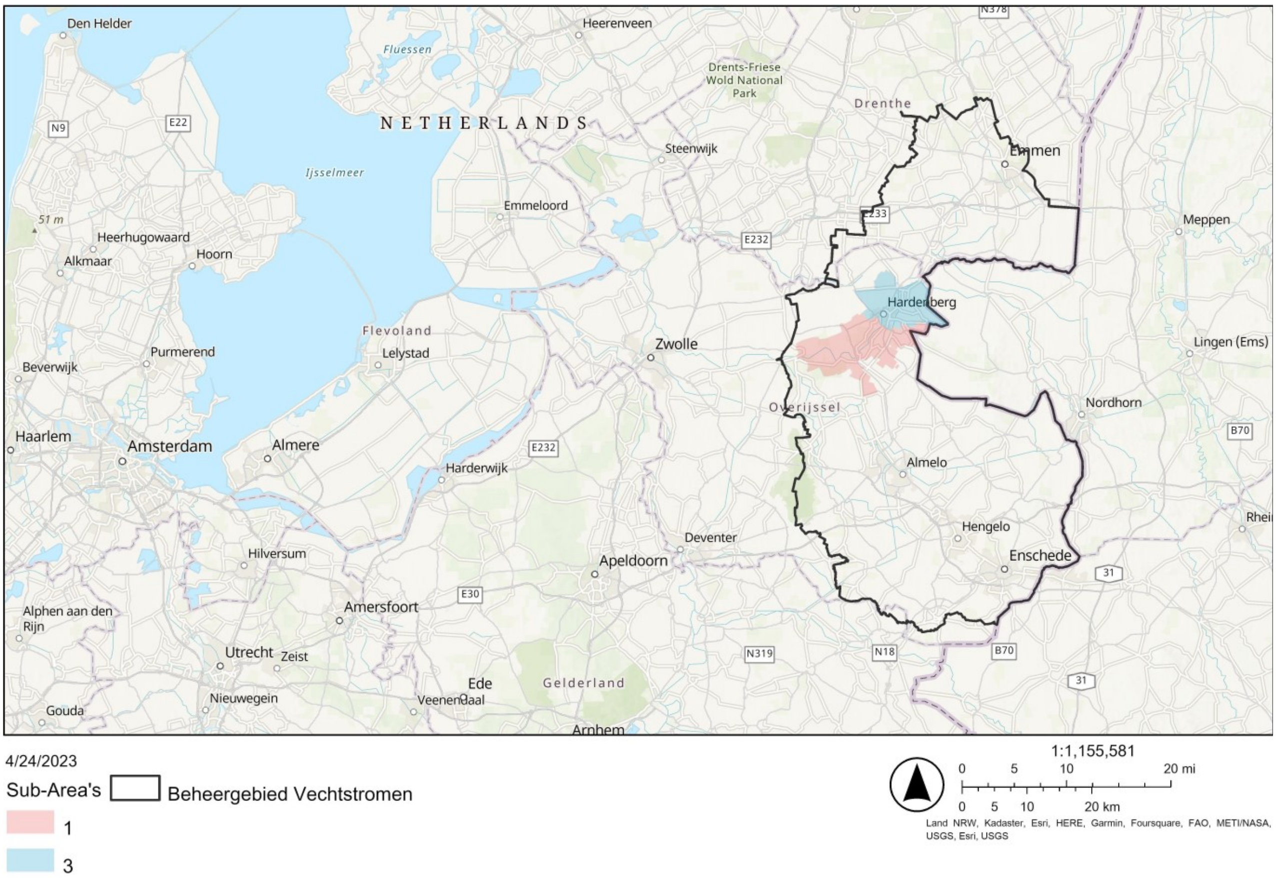


Figure 2: Area managed by the Vechtstromen Waterboard

For the measuring network, the waterboard has split it's managerial area into two sections, north and south. This was mostly done for practical reasons. The northern part, which used to be the former waterboard Velt and Vecht, was updated first with new measuring equipment. A detailed map of the northern part with it's subcatchments can be found at appendix A.1
The Southern part was the working area of the former Regge and Dinkel waterboard. A detailed map of the southern part with it's sub-basins can be found at appendix A.2

The area which this thesis will focus on is based on two sub-basins located in the northern part of the managerial area, basin 1 and 3. The basins are connected to each other, with the the Vecht rivers flowing right trough both. Both Afwateringskanaal and the Mariënberg-Vechtkanaal join the vecht in the projectarea.

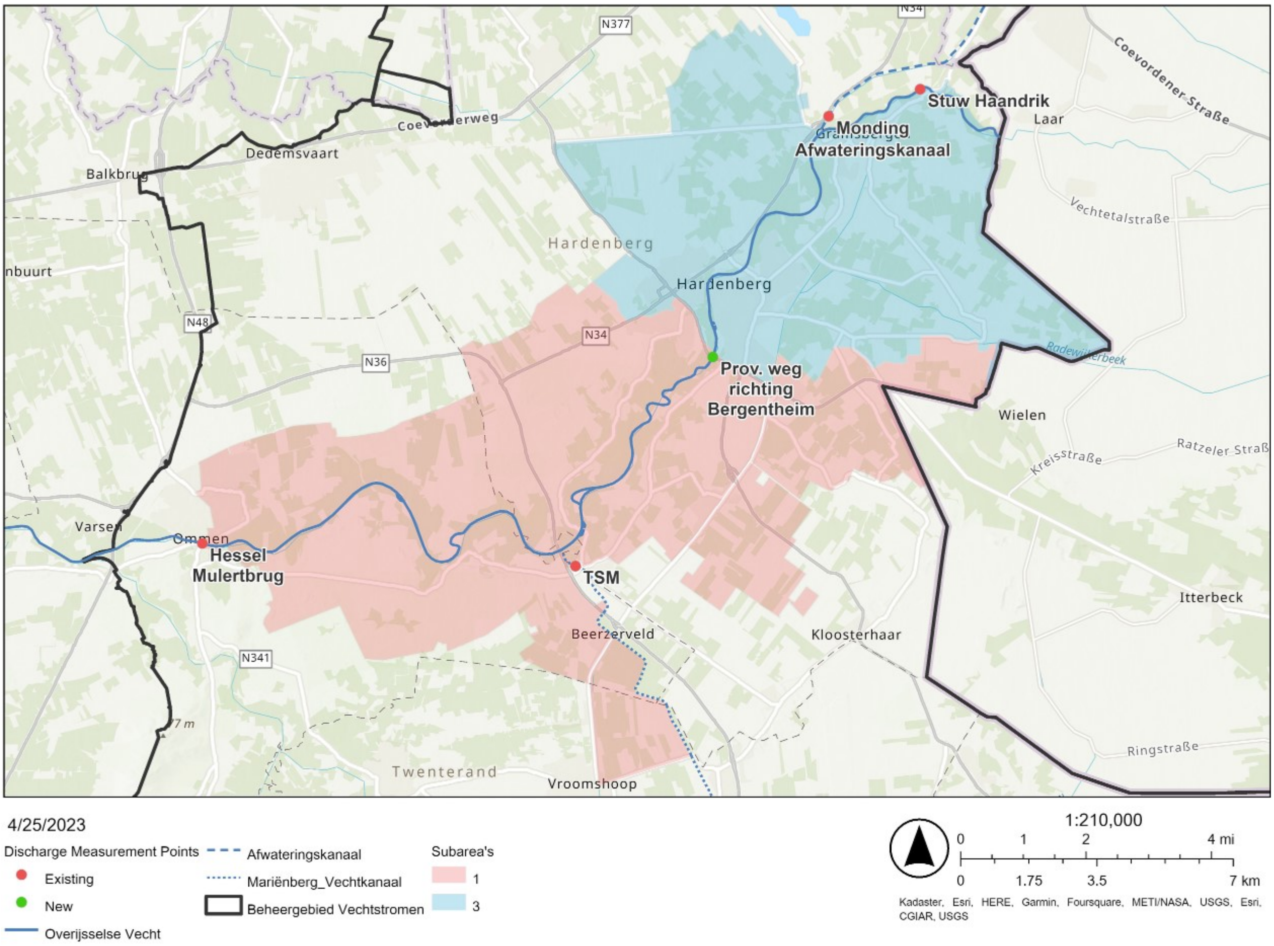


Figure 3: Project area with measuring stations

Because of their fortunate location, and the wide availability of data from monitoring stations, these two subareas were chosen as study areas.

2.2 Measuring stations

Currently, there are four existing operational measuring points in the project area. The discharge is measured by the measuring stations by using a riverbed profile, which gives an indication of the cross-section of he river. Multiplying the cross section of the respective river by the speed the water is flowing, results into the discharge in m^3/s.

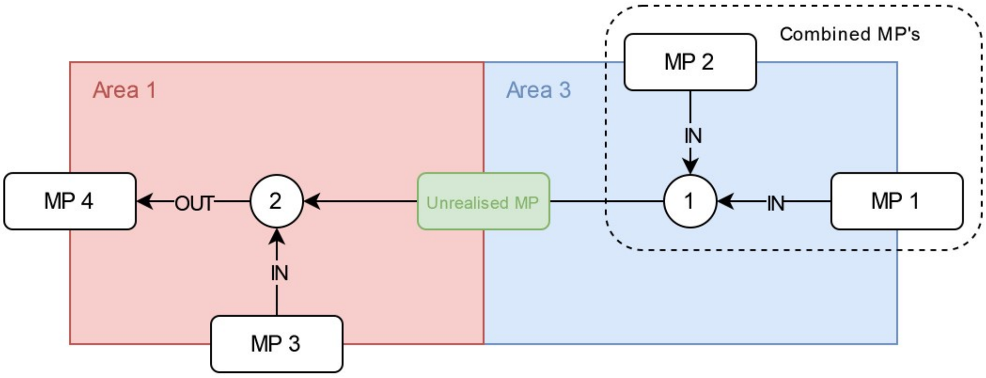


Figure 4: Rough scheme of the in and outflow

MP1: **Stuw haandrik**, This is a measuring point which can be seen as an inlet into the area, measuring the inflow of water into the Vecht. The measuring point is located close to the weir, but is denoted as the Stuw Haandrik Measuring point. Close to this stuw, the Overijsselse Vecht crosses the Coevorden-Vechtkanaal. The Coevorden-Vechtkanaal changes into the Overijssels Kanaal, while the Vecht continues it's path. Since the Overijssels kanaal is not part of the area (not seen as discharge point), it does not need to be measured.

MP2: **Monding afwateringskanaal**, is a measuring station measuring the discharge coming from the Afwateringskanaal into the Vecht. Together with stuw haandrik, it could be assumed that these inlets accounts for the total discharge which flows into the system from the Overijsselse Vecht, which is visualised in figure 4.

MP3: **TSM**, This measuring point is located near a weir, and is the is the third inflow into the system, close to Mariënberg. This covergence is relatively closer to the outlet then the inlet, and forms an input into subarea 1. The water is partly coming from the canal

MP4: **Hessel Mulertbrug** Located in Ommen, This measuring point can be considered the outlet measuring station, measuring the discharge of surface water out of the system.

In the near future, an additional measuring station will be realised, located between area 1 and area 3:

UMP **Prov. weg richting Bergentheim**, is going to be a measuring station located close to the provincial road N343 (hence the name), and will be realised in the near future (date not exactly known). This measuring point can be of great use for validating the parameters used for the model. This is done by creating a theoretical measuring station, which tries to simulate the values which could be measured at this discharge station. When in the future the measuring station is realised, it is possible to compare the expected/theoretical values to the measured values, to see if the model functions properly.

2.3 Points of interest

2.3.1 Convergence Afwateringskanaal and the Vecht

The convergence of the Afwateringskanaal and the Vecht is located close to the border in de upper side of the project area. In Figure 4, this convergence is denoted as (1). The amount of water flowing from Afwateringskanaal into the Vecht is of the same order size as what flows through the Vecht itself, this can be clearly seen in figure 5

Figure 5: The convergence: Afwateringskanaal on the left, the Vecht on the right (Photograph taken by author on 28-5-2023)

This convergence makes in possible to combine two measuring points in the area as one in the system. The runoff area between the drainage canal and the Vecht River is so small that the amount of precipitation that falls in the area here (some of which flows into the drainage canal before the measurement point anyway) is insignificant to make large differences in the water balance.

2.3.2 Convergence Mariënberg-vechtkanaal and the Vecht

In this convergence, water flowing from the Mariënberg-Vechtkanaal, which is mostly water coming from the upper southern areas, and a restricted/managed flow coming from the Kanaal Almelo-De Haandrik. It is denoted as (2) in figure 4.

2.3.3 Kanaal Almelo-De Haandrik

Kanaal Almelo-De Haandrik is a canal flowing through the project area, and is a side branch of the Overijssels kanaal. It originates at De Haandrik, where the Coevorden-Vechtkanaal and the Vecht converge. At Almelo, the canal merges with the Overijssels Kanaal, hence the name. The canal is not explicitly hightlighted in figure 3, but can be seen as white line showing underneath the meandering Vecht.

Figure 6: Height difference between Kanaal Almelo-De Haandrik and it's surrounding waterways (Photograph taken by author on 28-5-2023)

To some extent, the canal may be of interest for water balance. It is possible that side streams flowing from the canal, or seepage processes, influence the amount of water in the Overijsselse Vecht. The height difference between the canal and it's surroundings is clearly visable at figure 6
Also, the canal has already made a name for itself as a 'Problem Canal'. Dredging work took place on the canal from 2011 to 2016. This allowed heavier ships to cross the canal. However, water from the canal leaked under the adjacent housing estates. As a result, roughly 400 homes in the area around Geerdijk and Vroomshoop were damaged by subsidence (Kraak, 2020).

Research institute Deltares investigated the possible cause of the damage to the homes, including whether piping or leaking of extreme amounts of water took place. According to the study, a temporary rise in groundwater took place, however, this does not appear to be relevant to this study as it had already been neutralised back to the original groundwater level after a week (Deltares, 2021).

3 Theoretical framework

In this section, the theory which has been used for a theoretical framework is discussed.

3.1 Water balance theory

One of the first mentions of the concept of a water balance comes from the works of P. Perrault's *De l'origine des fontaines* from 1674, which mentions a linear dependence between the river runoff depth and precipitation depth (Perrault, 1674).
Dooge, 1968, mentions that a hydrological system can be devided into multiple subsystems, but also with different variances. According to Dooge, if hydrological systems are considered on a large scale, they can be considered closed systems. However, this is not the case in reality, because at smaller scales some elements are omitted (such as meteorological processes) and these are considered as inputs and outputs for a model.

With this in mind, the following can be stated (de Ridder and Boonstra, 1994):

$$\text{inflow} = \text{outflow} + \text{change in storage} \tag{1}$$

The general water balance equation can be written down as follows:

$$P + I = ET + Q + \Delta S + \Delta G + \Delta W \tag{2}$$

where P is precipitation, I the inflow (the water flow entering the respective area), ET the evapotranspiration, Q the outflow (the water flow leaving the respective area), and ΔS, ΔG and ΔW the changes in the water content of soil (unsaturated zone), groundwater storage (saturated zone), and water amount stored into surface water bodies (Sutcliffe, 2004).

In this case, it is not suitable for an real-time based basin/catchment model, since it misses two important variables. The model input data is often based on time interval (for example, a polling time of 5 minutes for rainfall events), an unit of time should be included into the equation. Also, there are no spatial boundaries or constraints this formula. Since precipitation events are not homogeneous (if it rains in Almelo, it does not necessarely mean it will rain in Enschede for example), a spatial boundary is required. This can be done by using the subsystems mentioned by Dooge, 1968, and the general water balance equation as mentioned by Sutcliffe, 2004.

De Ridder and Boonstra, 1994, have set up an equations for each subsystem, and also combined these into one general equation:

$$P - (E_o + E) + 1000\frac{Q_{si} - Q_{so}}{A} + 1000\frac{Q_{gi} - Q_{go}}{A} = \frac{\Delta W_u + \Delta W_s}{\Delta t} + \mu\frac{\Delta h}{\Delta t} \tag{3}$$

Symbol	Unit	Description
P	$mm/\Delta t$	Precipitation for time interval
E_o	$mm/\Delta t$	Evaporation for land surface
E	$mm/\Delta t$	evapotranspiration from unsaturated soil
Q_{si}	$m^3/\Delta t$	Lateral inflow of surface water into the system
Q_{so}	$m^3/\Delta t$	Lateral outflow of surface water out of system
A	m^2	Area of the system
Q_{gi}	$m^3/\Delta t$	Groundwater inflow into the system
Q_{go}	$m^3/\Delta t$	Groundwater outflow out of system
ΔW_u	mm	Change in ground water storage
ΔW_s	mm	Change in surface water storage
μ	-	Effective porosity as fraction of volume of the soil
Δh	mm	Change in water level over Δt

Table 1: Symbols of equation 3 with their units and description

3.2 Groundwater processes

3.2.1 Porosity

Soil porosity refers to the empty spaces within soil particles that allow for the movement of air, water, and roots. It plays a crucial role in hydrology, affecting the movement and storage of water in the ground. Highly porous soil facilitates water infiltration and groundwater recharge. Conversely, compacted or low-porosity soil hinders water absorption, leading to surface runoff. The porosity of a sandy soil is at avarage around 40% (Olsthoorn, 1977)

3.2.2 Groundwater in the soil

Groundwater exists in two distinct layers: saturated and unsaturated zones, each with unique properties that play a crucial role in the overall water balance of an area.

The saturated zone is located beneath the water table, where all the available pore spaces are filled with water. It acts as a storage reservoir for groundwater, replenished by recharge from precipitation, rivers, and other surface water sources. The saturated groundwater exhibits hydrodynamic behavior, allowing for the free movement of water and creating aquifers that can be tapped through wells or springs. Its properties, such as hydraulic conductivity and porosity, influence the rate at which water is transmitted through the subsurface, affecting the overall water balance of the region.

Above the water table lies the unsaturated zone, also known as the vadose zone. In this zone, the pore spaces contain both air and water. The unsaturated groundwater plays a vital role in the water balance by serving as an intermediary between the land surface and the saturated zone. It undergoes capillary action, allowing water to be held against gravity within the narrow spaces between soil

particles. This zone functions as a buffer, regulating the movement of water and facilitating the filtration and purification of percolating water before it reaches the saturated zone. The unsaturated groundwater is subject to evaporation, plant uptake, and infiltration into the saturated zone, influencing the overall water balance of the ecosystem (Bear, 1988).
This information can be summarized into a scheme, as seen in figure 7:

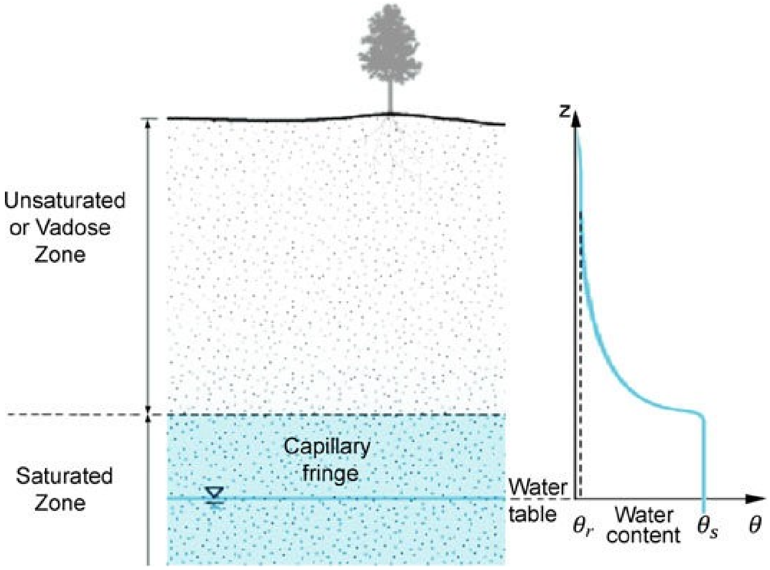


Figure 7: Vadose and Saturated zone scheme, including water table (Wang and Manga, 2021).

3.2.3 Groundwater seepage

Darcy's law can be used to determine any seepage coming from a situation were there is a difference in water level head pressure. This may be especially the case at locations where the water level is kept artificially higher then it's surrounding environment water level, for example around canals. The flow rate of water seepage can be calculated by the following equation:

$$v = ki \tag{4}$$

Where v is the water seepage flow rate in cm/s, k is the seepage factor of the soil in cm/s and i is the head loss coefficient. This head loss coefficient can be calculated according the following equation:

$$i = \frac{\Delta h}{L} \tag{5}$$

Where Δh is the head difference in meters, and L is the difference between the two water bodies, also in meters (Das and Sobhan, 2014). This can be combined into the following equation:

$$v = k\frac{\Delta h}{L} \tag{6}$$

Values for k can be found in appendix section B.3. The flow in m^3/s can therefor be determined by dividing the outcome of the equation by 100, and multiplying it by the river bed surface area expected to be responsible for seepage and the length of the river.

3.3 Evaporation and evotranspiration

Evaporation and evapotranspiration are interconnected yet distinct processes. Evaporation is the conversion of water from a liquid to a gas, occurring primarily from water surfaces due to solar energy and temperature. Evapotranspiration, on the other hand, includes evaporation and transpiration. Transpiration is when plants release water vapor through stomata. Evapotranspiration is influenced by solar radiation, temperature, wind, vegetation, soil moisture, and plant health. (Gulliver et al., 2010)

3.3.1 Makkink potential evapotranspiration

The Makkink potential evapotranspiration formula is used by the KNMI to determine the amount of evapotranspiration for a system. This formula was derived and simplified by Makkink from the Penman formula, since Penman equation uses difficult to determine variables, like the latent heat of vaporization λ_v (in MJ/kg) and the slope of the vapor pressure curve (Penman, 1948). The penman equation makes use of the conditions of the atmossphere, . These values are often difficult to determine, hence Makkink has set up a formula to make the determination of evapotranspiration easier. The main difference between the penman equation and the equation makkink derived from it, is that the result of the Penman equation is a potential evapotranspiration The equition which followed can be denoted as follows:

$$\lambda \cdot E_{ref} = C_1 \cdot \frac{s}{s+\gamma} \cdot K_{in} + C_2 \tag{7}$$

Symbol	Unit	Description
λ	-	Heat of evaporation of water (2.45E6 J/kg at 20 degrees Celsius (℃))
E_{ref}	$kg/(m^2s)$	reference crop evaporation
C_1	-	Constant (de Bruin, 1981 found a value of appr. 0.65)
C_2	-	Constant (de Bruin, 1981 found a value of appr. 0)
K_{in}	W/m^2	Shortwave radiation
γ	-	Psychrometerconstant (appr. 0.66 mbar/℃ at sea level)
s	$mbar/$℃	The derivative to temperature of the saturation vapor pressure
T	℃	Temperature

Table 2: Symbols of the Makkink Equation (Makkink, 1957)

The values s still remains unclear in the Makkink equation, but can be derived as follows:

$$s = \frac{a \cdot b \cdot c}{(c+T)^2} \cdot \exp \frac{b \cdot T}{c+T} \tag{8}$$

Symbol	**Unit**	**Description**
a	$mbar$	Constant with a value of 6.1078
b	-	Constant with a value of 17.294
c	C	Constant with a value of 237.73
T	C	Temperature

Table 3: Symbols and their values for the determination of s

This makes that the Makkink equation only requires two measurable values, the Temperature and the short-wave radiance, but some adjustments may be required (e.g. Heat of evaporation when the temperature is not 20 degrees celsius). The formula can be rewritten such as only the reference crop evaporation is an output.

It should be considered that evapo(transpi)ration is not the same value for each surface. Certain crops or vegetation have different properties, which make it possible that at the same weather circumstances, a different amount of water evaporates between different surfaces. Feddes, 1987 has set up crop factors in relation to Makkink reference-crop evapotranspiration, This resulted in a list of seasonal depended constants for a wide range of crops and vegetation found in the Netherlands. This constant can be applied by the following formula:

$$E_{opt} = k_c E_{ref} \tag{9}$$

Where E_{opt} is the optimal crop evapotranspiration value, and K_c is the crop factor (Doorenbos and Pruitt, 1977). Since the resulting evapotranspiration is still a potential evapotranspiration in the case of an optimal performing vegitation, there is a possibility that the real evapotranspiration may be significantly off compared to Makking-determined evapotranspiration. The uncertainty in the yearsums of the actual evapotranspiration compared to the makkink determined evapotranspiration values is between 10 and 15 % (Elbers et al., 2010).

3.3.2 Evapotranspiration in relation to precipitation

A more elementary way of approaching evaporation is to calculate, on an annual basis, a certain percentage of total precipitation as evaporation (Bos-Burgering et al., 2020). This means in the case where 600 mm evaporates, and 70 percent of the precipitation evaporates, there is 420 mm of evaporation. However, this reasoning does not work when looking at a more detailed resolution, since then seasonal effects, such as the increase in solar radiation in summer, are omitted. One of the major advantages of this method is the fact that no complicated calculations have to be done, and no solar radiation data or temperature data are required .

3.3.3 Evapotranspiration by agricultural activities

Irrigation of crops, which is the main land use cover of the area, is mostly done by pumping up groundwater, especially during dry seasons. Around 65 to 85% of the water used for irrigation in the Netherlands is acquired by pumping up groundwater (Hoogeveen et al., 2003) . The average amount of groundwater usage per year per agricultural oriented farm on average is estimated to be 1300 cubic meters per year (van der Meer, 2018). The groundwater that is pumped up and used to irrigate crops is partly absorbed by the crops themselves, but some also flows back into the earth. Two forms of evaporation then take place here. evaporation of moisture from the plants, and evaporation from the upper, unsaturated layer of soil. In this way, irrigation of crops by farmers indirectly contributes to evaporation (Wanniarachchi and Sarukkalige, 2022).

3.4 SPEI drought index

The Standardized Precipitation-Evapotranspiration Index (SPEI) is a relatively new index that can be used to determine how dry a year was. Unlike other indices that rely solely on precipitation data, SPEI also takes into account evapotranspiration, which is the combined loss of water from the land surface to the atmosphere through evaporation and plant transpiration. It is currently used by the KNMI, to categorise years based on how dry they were.

SPEI values are useful for understanding the severity and duration of drought conditions. A negative SPEI value indicates that the precipitation deficit is greater than the water loss due to evapotranspiration, indicating a period of water stress. In contrast, a positive SPEI value indicates that there is more water available than is needed, which could lead to flooding or other water-related issues.

Value	Meaning
2.0	Extremely wet
1.5	Very wet
1.0	Wet
0	Normal (average 1965-2020)
-1.0	Dry
-1.5	Very dry
-2.0	Extremely dry

Table 4: SPEI values and their meaning

These SPEI values can be based on different invals: SPEI-3 would indicate a 3 month interval based SPEI value, while SPEI-12 would take a normalised 12 month period into account. SPEI-12 is therefor more useful for determining long-term droughts (Vicente-Serrano et al., 2010).
The SPEI values will be further discussed in section 4.3.2.

4 Methodology

Due to the demands of the water board for an applied model, the approach to develop a model in the programming language python has been choosen. There has been attempts to look at current existing models, but these did not seem suitable for the goal of this research. Flexibility is one of the main reasons why developing a completely new model is done. This makes it possible to add features to the model later on based on previous results, following a form of a design cycle.
These properties define the orientation of the research, hence the method focuses mainly on the process required to develop a model for water balances. The quality of the data is mostly based on how it is processed and calibrated.

A part of this methodology is lousely based on the three cycles of Hevner, 2007. Hevner states that, according to Design Science Research principles, three seperate cycles can be deducted. The relevance-, design- and rigor cycle.
Design Science Research is a problem-solving approach that combines design thinking and scientific methods to develop and evaluate innovative solutions to complex problems in various domains. It is commonly applied in fields such as information systems, computer science, and engineering (Simon, 1970).The primary goal of Design Science Research is to create and validate knowledge through the design, development, and evaluation of artifacts. These artifacts can take the form of new technologies, processes, models, frameworks, or theories that address specific problems or challenges. The research process typically involves iterative cycles of design, implementation, evaluation, and reflection (Simon, 1988).

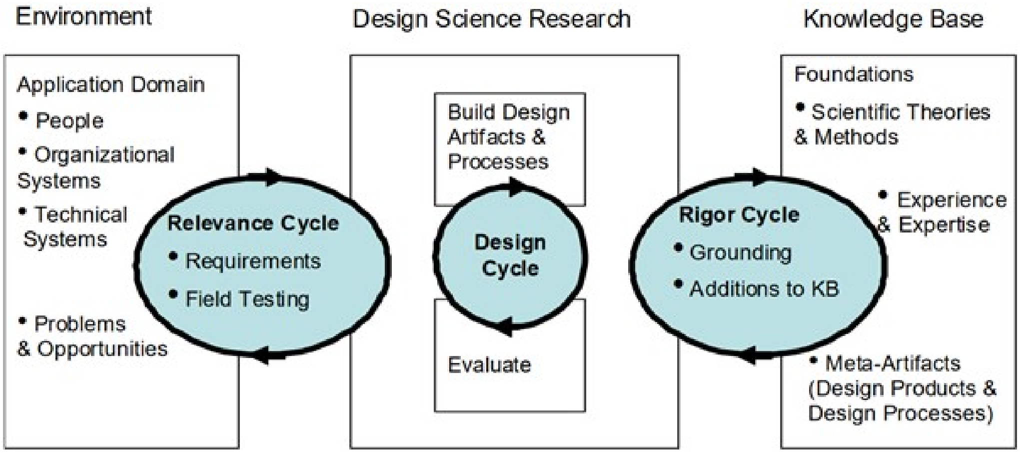


Figure 8: The three cycles of Design Science Research (Hevner, 2007)

The final model is used as a tool to generate output data, namely water balances and other secondary outputs, but can also be seen as separate output of this research. To some extend, the resulting model is again part of the method itself, creating an interesting connection between the two output types.

4.1 Method outline

The method for this study can essentially be divided into three separate pieces, each representing a phase in the process towards an end result. The research questions are mainly answered in phases two and three.

The first phase can be seen as an orientation phase in which criteria are set, the environment is studied, and the first processes important for a water balance are examined. This phase consists of two groups:

1a **Model criteria**

1b **Preliminary model design**

From this follows the design phase. The phase in which the model is built based on theory, data is collected and checked, and it is considered how this can be modelled. Finally, based on uncertainties, it is then considered whether it is possible for the model to produce the water balance at a detailed resolution. This phase can be repeated several times, can be seen as a kind of modelling cycle, and consists of 5 groups:

2a **Setup theoretical framework**

2b **Data gathering and analysis**

2c **Programming and model building**

2d **Uncertaincy and resolution**

I ***Miscellaneous programming***

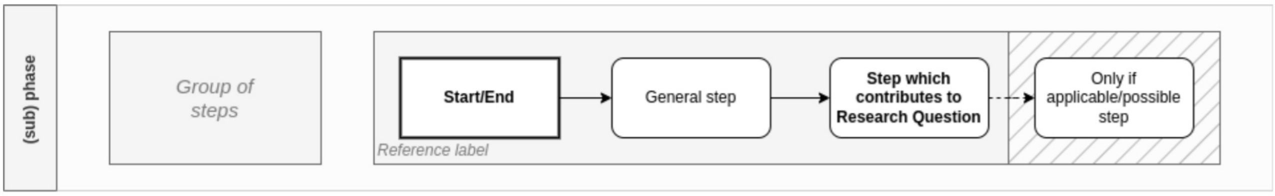
The third phase begins when it is no longer possible to have the model generate more detailed output. Here we then look at possible validation, and the generation of data and figures that can be used for the report. This phase consists of 3 groups:

3a **Validation**

3b **Presentation**

II ***Output programming***

This information can be schematized as seen in figure 9, on the next page:



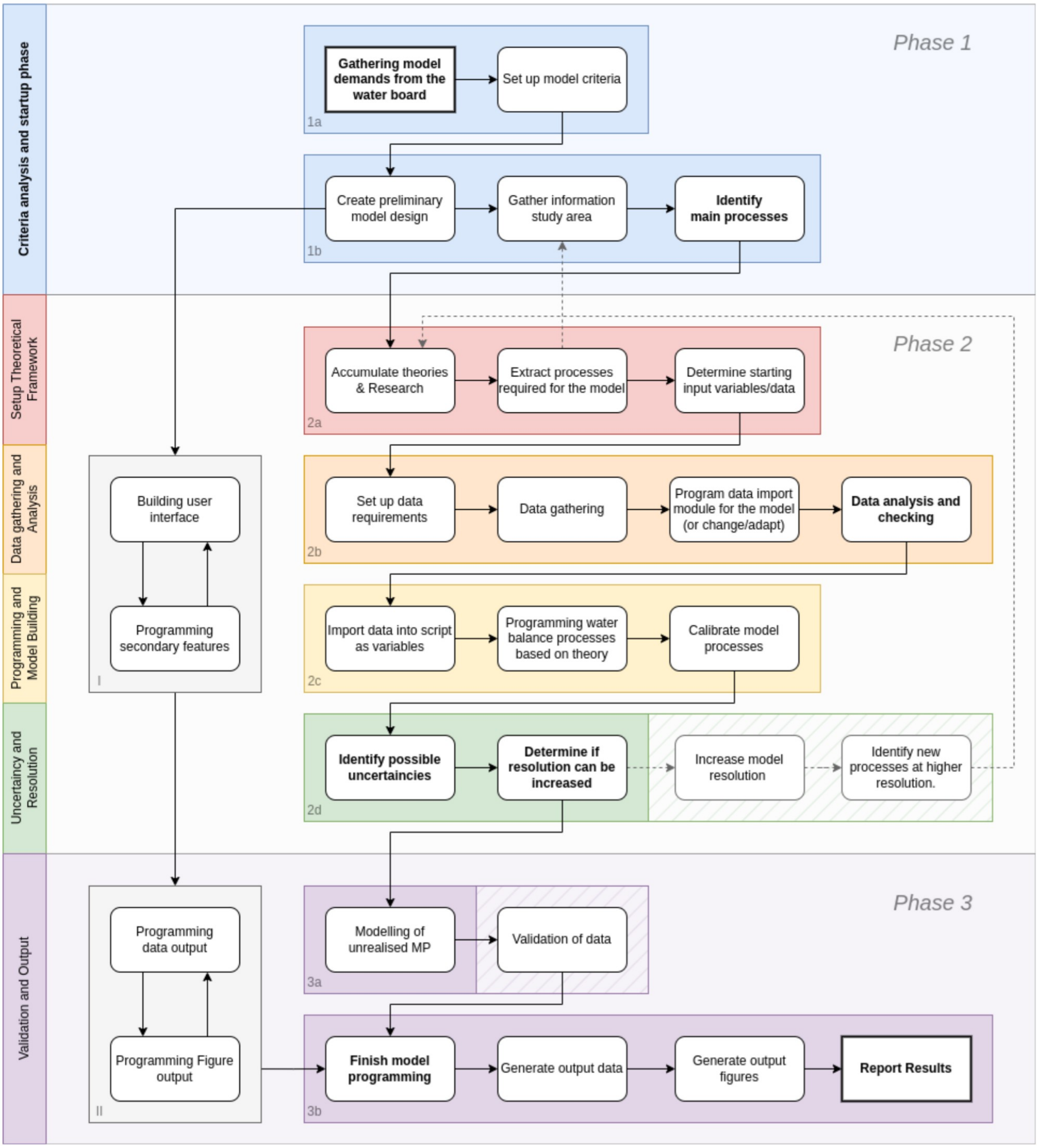


Figure 9: Schematic of methodology

4.2 Orientation phase

4.2.1 Model criteria (1a)

To provide a scope for the model building process, a list of discrete requirements that the model would have to meet was drawn up, mostly based on the demands of the water board.

The model must...

- ... be able to digest a wide range of data on different time intervals (e.g. hours versus days). This adapts to the fact that the gathering of data may not lead to homogeneous results when looking time intervals.
- ... be able to run quick and be efficient. This means that the model must not need 5 minutes to initiate one run, and should preferably have running times in the range of seconds. This requirement is important, mostly due the fact that the model also needs to be calibrated, and is is fortunate to be able to quickly change parameters when calibrating the model.
- ... be flexible and have a modular approach. A modular approach makes it possible to easily include certain processes (like groundwater processes), or leave them out when deemed not necessary, to make model runs go quicker.
- ... be able give indications for possible errors in measuring points through graphs and data
- ... be able to model an unrealised measuring point, which will be between area 1 and 3, to validate results.
- ... be user-friendly. Therefore, the model needs good documentation, so it may be used by the water board when the thesis is finished. A Graphical User Interface (GUI) would be ideal for such model. A GUI makes the model easier to handle, since the user is not directly confronted by the code the model resembles. Instead, the user can use a seperate window or webpage to fill in user input or include data.

4.2.2 Preliminary model design and information gathering(1b)

Based on the model criteria, a preliminary model design was drawn up in advance. This gives a rough idea in advance of what the model should look like, and helps with building the model. The preliminary model structure consists of three main components: an data input part where data is processed, a data processing part where (water balance) theory is applied, and a data output part where the results are presented in an understandable format. Secondly, based on study area investigations and research, a list of processes which are relevant for water balances was set up. In this phase, it was also determined that the model would be written in Python, due to it's open-source nature and the broad accessibility of documentation and guides.

Preliminary model design result

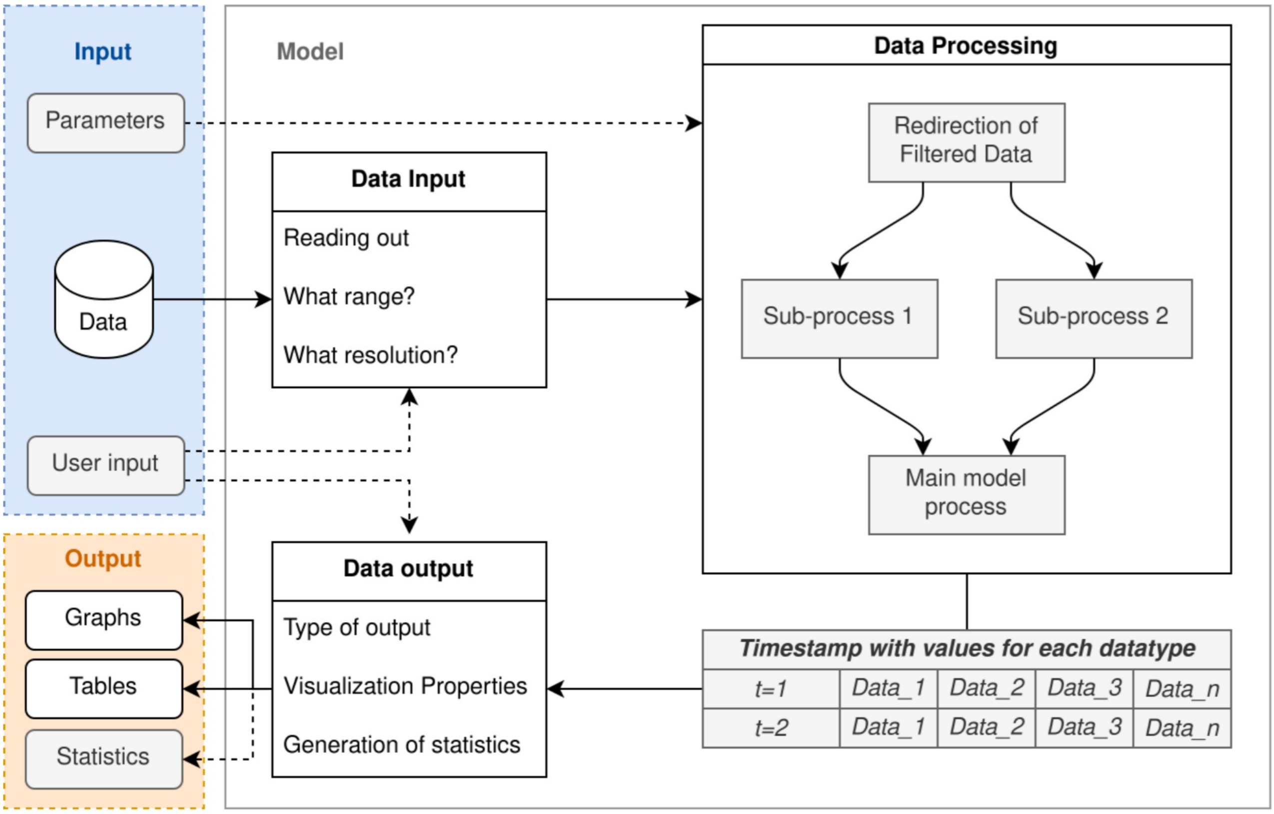


Figure 10: Preliminary model design

Input

In the blue rectangle, all the input data which is required is summed up. The model requires 3 types of input:

1. **Parameters**. During the processing part of the model, equations acquired from the theory in section 3.1 are applied to the input data to simulate the hydrological processes that simulate the movement and distribution of water. These equations typically include several parameters that describe the physical characteristics of the study area.

2. **Data**. This data is the input for the model and could represent variables like precipitation, evaporation, land-use, discharge, or evapotranspiration.

3. **User input**. The user of the model needs to input certain values like the desired time range and resolution, but also the desired output format (graph type etc.).

This input is processed in the Data Input section, in which the user input is used to select the right range of data which should be run through the model. Here, hourly data can be translated into daily data for example. The main user input which is required here is mostly related to what range of data is going to be used, and the respective resolution which should be applied (day, week, month, etc.).

Data Processing

The data processing is done by splitting the data into different sections. Each type of data is treated different, and will be processed such as it can be used into the main model process (the water balance equation). Figure 10 simplifies this by just two processes, but in reality this is more complex. Different types of input data can be merged, such as precipitation data and land use, to combine a final output which is then again used in the main model process.

Output

The output can be divided into three different types:

1. **Graphs and visualisations**, based on the input parameters of the user.
2. **Tables and output data**, for storing the results or further processing.
3. **Statistics about the model** (e.g. time of a run) or other relevant factors. This can be quite useful to check if the model complies with the model criteria.

The outputs are result of the Data Output section of the model. The type of output is specified here, together with the visualization properties as result of user input. The data about the operation of the model (like running times) are processed at the Data Output section, and will be used for measuring the efficiency of the model.

Gather information study area

Most information about the study area was gathered by using the information provided by the waterboard Vechtstromen. On the 28th of may 2023, due to a knowledge gap, a field study was conducted. Observations of loss of discharge from the Almelo-de Haandrik canal were considered in this field study. This may affect the discharge flowing out of the system. A bicycle ride along the Canal and the Vecht was therefore used to specifically look for discharging flows that are not noted. Several photographs were also taken of the project area to supplement this thesis. These are listed throughout the report. Also, there are additional photos in the appendix, section E.

Identified Processes

The following processes were identified based on gathered information from the study area:

- Precipitation
- Evapotranspiration
- Discharge from multiple sources
- Water storage, both groundwater and surface water.
- Vertical groundwater flows
- Sewage Treatment Plants operating in the area
- Seepage (from head difference), originating from the Almelo-De Haandrik canal
- Agricultural influences and effects, mostly irrigation

Most of these processes are fairly self-explanatory, e.g. precipitation and evaporation. Some other processes have been investigated further, such as the possible influences of sewage treatment and activities of farmers. The role which they might play in the model will be shown in the results. For a large extend, it was already clear in this phase what the biggest hydrological processes were, which **supports the answering of Research Question 2a**. Later in this research, the results of the identification of the main processes can be confirmed after actually translating data into clear outputs.

Figure 11: Agricultural activities in the project area. (Photograph taken by author on 28-5-2023)

4.3 Design and model programming phase

4.3.1 Theoretical Framework (2a)

Based on the identified processes coming from the orientation phase, the necessary literature had been gathered. Most of the literature is gathered from online articles, but also physical books were accessed. From this theory, the processes and formula's which were relevant for this research, were extracted. This also meant that sometimes, more information about the study area was needed. This resulted in going back to the preliminary model design group of steps. A nice example was the investigation of seepage due to the head difference from the Almelo-de Haandrik canal. The outcomes will be discussed in the results section.
Also some background literature about waterbalances from Hoogheemraadschap De Stichtste Rijnlanden which provided information about the possibility of setting up water balances (van Buren et al., 2008), proved as useful (background) reading material.

4.3.2 Data gathering and analysis (2b)

Set up data requirements

Before collecting data, the criteria the data should meet were examined. Since the most common resolution for many data is measured on a daily interval basis, it was chosen to set this as the minimum requirement for selecting data. Also a sufficient time range had to be chosen. This has been done based on looking at SPEI-12 values of the past years. A range from the beginning of 2017 until the end of 2022 has been chosen, since this time range contains different years with vastly different SPEI values. SPEI values have been described in section 3.4.

The values for the chosen years are:

Year	2017	2018	2019	2020	2021	2022
SPEI-12	0.2	-1.9	-0.2	-0.3	0.3	-1.3

Table 5: SPEI-12 values within the data range

Most of the data used for this research is collected by research institutes, such as KNMI, TNO, and the water board itself. Little data was available from other parties, which makes it not particularly possible to compare data. Unfortunately, this also meant sometimes having to settle for data that may not have been entirely of desired quality.

The following datasets were used within this research:

Name	Origin	Content	Interval	Start	End
DM Afwateringskanaal	Vechtstromen	Discharge meas.	Hourly	1-1-2017	9-5-2023
DM de Haandrik	Vechtstromen	Discharge meas.	Hourly	21-7-2017	9-5-2023
DM TSM	Vechtstromen	Discharge meas.	Hourly	1-1-2017	10-5-2023
DM Vecht Ommen	Vechtstromen	Discharge meas.	Hourly	1-1-2017	9-5-2023
GW Groeneveldweg	TNO	Groundwater level	Hourly	22-11-2014	22-4-2022
GW Hunne	TNO	Groundwater level	Hourly	15-11-2014	4-4-2022
GW Rauwbloksweg	TNO	Groundwater level	Hourly	25-11-2014	4-4-2022
Neerslaggeg. Heino	KNMI	Precipitation	Daily	1-5-1930	20-3-2023
Neerslaggeg. Twenthe	KNMI	Precipitation	Daily	1-5-1930	20-3-2023
Neerslaggeg. Hoogeveen	KNMI	Precipitation	Daily	1-5-1930	20-3-2023
Verdamping Heino	KNMI	Evapotranspiration	Daily	1-1-2016	1-5-2023

Table 6: Datasets used for the model

Program data import module

Before the main model was build, a python function was made which could easily import different types of data as a dataframe. A dataframe is a common type of entity used in the programming language python, and is able to maintain the date/timestamp of datapoints from a dataset.

After importing the data, it is possible to analyse the quality of the data. Outliers, missing data or incorrect data can be selected and used for a possible future uncertaincy determination. Therefor, **this step provides answers for Research Question 2b**.

4.3.3 Programming and model building (2c)

After the data analysis was done, the programming of the model has started. First, the data import function, mentioned earlier, was used to import the data into the newly created python script. The data got variables assigned, so it becomes easily accessible from within the model
From here, the theory, accumulated in step 2a, was used and converted to code. This was
This resulted in a range of parameters which could be calibrated to better fit the properties of the project area.

4.3.4 Uncertainty and resolution (2d)

Identify possible uncertainties

After the calibration of model processes, possible uncertainties were addressed. The main sources which were addressed for uncertainties are:

- Approaching the processes drawn up in the orienteering phase to a theory that adequately covers the process. Here, we can look at, for example, certain processes that may be fairly easy to explain through theory, but on closer inspection may still be more complex than expected. simplifying these may potentially introduce uncertainty.

- Translating the theory into correct code. Because not every theory can be translated directly into adequate code, and certain things may have to be assumed, uncertainty may arise from the re-omission of potentially important details
- Uncertainties directly reflected in the dataset. There may be that missing in the dataset that results in an incomplete picture of a particular process due to a few missing data points, for example.
- Indirect inaccuracies in the dataset due to instrumental errors.Instrumental errors can, for example, cause discharge data to be structurally too high or too low. This may cause data to be interpreted incorrectly, while in reality it may be different.
- Programming errors and rounding errors. In this case, this can happen by calling the wrong variable, as well as forgetting a comma or dot. Also rounding of values multiple times could create discrepancies in the output results.
- Incorrect assumptions can cause certain things to be misinterpreted, e.g. because they are taken out of context or used incorrectly. This can result in data that looks good at first sight, but may turn out to be incorrect

Also one uncertaincy was already known before this research, and was also taken into account during the design phase of the research:

- An internally available report conducted by consulting firm AquaVision, speaks of structural over-measurement of flow through the discharge measuring point at the Hessel Mulertbrug in Ommen. This is said to be partly due to the use of an incorrect river floor profile, which overestimates the measurements by 20 percent (Bijlsma, 2022).
  This uncertaincy belongs to the instrumental error type of uncertainties/errors.

Determine if resolution can be increased

After each round in the modelling cycle, a check was done to see if any of these uncertainties took place in the state of the model. Also new uncertainties were identified, and other possible complications which could hinder the process of increasing the resolution of the model. When this was not the case, and the model still gave suitable results, the resolution of the model was increased, to then go through the model cycle again. When it was not possible to increase the model resolution, due to complications in the modelling cycle, the modelling cycle was aborted and the third phase would start. **With the results of this step, Research Question 2c can be answered.**

4.3.5 Miscellaneous programming (I)

The model is not ready if only hyrological processes are programmed. Other functions must also be written that contribute to the criteria set for the model. This can be divided into 2 parts, namely a user interface (GUI) part, and a part with secondary functions and capabilities required by the model.
For the user interface, a python module called TKinter was used, which enables the creation of a high-quality user interface by using python code. Various parts of the model are brought under

this, but mainly these are things that require user input. This could include adjusting parameters or switching modules on and off in the model.

Some secondary functions have been written that have little impact on the outcome of the model, but mainly take care of peripheral issues. These might include, for example, some functions that control statistics, or a function that calculates averages that can be used for calibration purposes. Also a temporary figure output function was made to easen the calibration and the identification of uncertaincies.

This phase is a continuous process, alternating between programming the user interface and secondary functions, mainly based on the requirements that arise from the general modelling cycle in phase 2.

4.4 Validation and output phase

4.4.1 Validation (3a)

Validation tends to be a difficult subject when modelling, especially when no alternative data can be used. Therefor, validation can only be done based on guidelines of the water board and comparing data with each other to get a better idea how the data performs relative to each other.

Hence the difficulties, most of the validation was done by modelling the unrealised measuring point in the model. This can be done by summing up all the processes which happen at the upper part of the area, and comparing it with the output of the second area, minus processes which occur there. If the average difference is zero, it can be concluded that this combination of different data proves to be sufficient for a water balance.

Secondly, the Flow rates guide sheet in appendix section B.1 is used to determine if the data which is measured in the measuring station is around the same values of what would be expected. This table was used to gather the relative inflow values. These values are the values of the inflow measuring points, relative to what flows out of the system at measuring station Vecht Ommen (hesselmulert bridge). These calculations can be found in appendix B.1. This resulted in the following values:

Measuring Point	Relative Value
De Haandrik	66.82%
DM Ane Gramsbergen (Afwateringskanaal)	20.44%
Marienberg-Vechtkanaal (TSM)	2.36%
Remainder	10.38%

Table 7: Measuring point values relative to the output

4.4.2 Presentation (3b)

Before the model can be put into use, and the results presented, some final touches were made. By cleaning up the model's code and incorporating some non-essential functions that contribute to usability. After this, practically nothing needed to be done to the model and the generation of the necessary output data could start. The process of answering research question 1 naturally plays out over the whole of phase 2, but is clearly answered when finalising the code of the model. **Therefore, this step answers Research Question 1 and Research Question 3**.

4.4.3 Output programming (II)

One of the most necesary elements of the model may be the output data. Therefor, a possibility to output this data from the model was deemed an important factor of the model. Due to As mentioned earlier, the ability to show figures was created earlier in the model. However, this still needs to be incorporated into the user interface, and these figures often lack essential components to be used in a report. It is also necessary to consider which figures are relevant to the end user. A special module was therefore programmed to ensure that figures can be displayed in the model on a selection basis. Here, we chose the most practical data that the end user might require, looking at the figures that can be found mainly in the literature.

4.5 Method per research question

The location where research questions are answered in the method are summarised here, by using the grouping system used by figure 9.

1. Which features and processes are incorporated into the the developed water balance model?
   This Research question is answered at **group 3b**, the presentation part of the method, at "Finish model programming".
2. To which extend can the water balance be closed with the developed water balance model?
   This research question can be answered based on the three subquestions, and the conclusions which can be drawn from the calibrated ouputs.
   (a) What are the biggest hydrological processes in the area?
   This research question is partally answered at group 1b, "Identify main processes", and is answered in **group 2b**, "Data analysis and checking". Using the observations made in the orienting phase, an initial estimate can be made about the largest hydrological processes in the area. These can then be confirmed using the data that has been collected and analyzed.
   (b) Which processes generate uncertaincy within the water balance?
   This research question is answered at **group 2b**, at "Data analysis and Checking", and at group 2d at "Identify possible uncertainties". Discovering sources of uncertainty naturally occur throughout the duration of the study, but mainly during the analysis of the data. These do get noted for further analysis later. It can be said that a data-driven model is very vulnerable to uncertainties in the data. From here it can be determined if these uncertainties found are significant in influencing the final result, or if further research may need to be done on these uncertainties.
   (c) What is the most detailed resolution in which the model still gives sufficient results?
   This research question is answered at **group 2d**, the uncertaincy and resolution part of the method, at "Determine if resolution can be increased". This question is answered by going through the modeling and design process, visible in figure reffig:method, and depends largely on the results coming from research question refq:uncertainties. At the point when the uncertainties in the process become too large, and it proves impossible to come up with useful results, it becomes clear to what resolution the model delivers suitable results.
3. How does the model support the water board in their operational water management?
   This research question is answered at **group 3b**, the presentation part of the method, at "Finish model programming". At this point it is clear what all has been implemented in terms of requirements from the water board, and how the model meets these.

5 Results: Model

5.1 Model explanation

This section explains how the model ended up looking, and attempts to represent its structure.

5.1.1 Functions

The model is set up as structured concatenation of multiple functions. These functions can be called by the user interface, or by other functions. Functions make the model code easy to understand and debug. There are practically five functions present in the model, one related to input (1), one related to processing (2) and three related to generating outputs (3,4,5). These functions are by no means all the same size, and are called in different ways. The following functions can be found in the model:

1. Import function, which ensures that data is imported and converted into a usable data set with the appropriate interval and resolution.
2. Model Function, which can basically be seen as the core of the model. It is called through the user interface, and is the first function called when the model is started. The model function again consists of two parts, a processing and an output part. Both of these parts are a collection of modules, which can be controlled through the user interface. More information about these modules can be found in section 5.1.2
3. Save Figure Function, which exports figures from the model to a file.
4. Save Data Function, which exports data from the model to a file.
5. Save Statistics Function, which exports the statistics and run information generated by the model to a file.

5.1.2 Modules

The core model function consists of different modules which can be easily turned on and off within the GUI. This makes it possible to quickly get selected information about certain issues in a water balance. For example, it is possible to display only the elements associated with weather events, such as precipitation and evaporation. How these modules exactly work, and how they have adapted the literature, is covered in the section 5.3. The Processing current modules are:

- Precipitation
- Evaporation
- Groundwater
- Discharge
- Storage

The for the output, it is possible to activate only one module at a time, since only one graph can be displayed in the GUI. More information about the output The following outputs modules are available in the model:

- Overview
- Relative Origin
- Discharge
- UMP (Unrealised Measuring Point)
- Storage

5.1.3 Model GUI

The model Graphical User Interface consists of two sides. On the left side, the user interaction and input is the main focus. On the right side, the output results are presented, with different types of graphs.

The user interaction side of the GUI consists again of two parts. An upper and a lower part. In the upper part, different settings and variables can be adjusted. This is structured acros three different tabs.

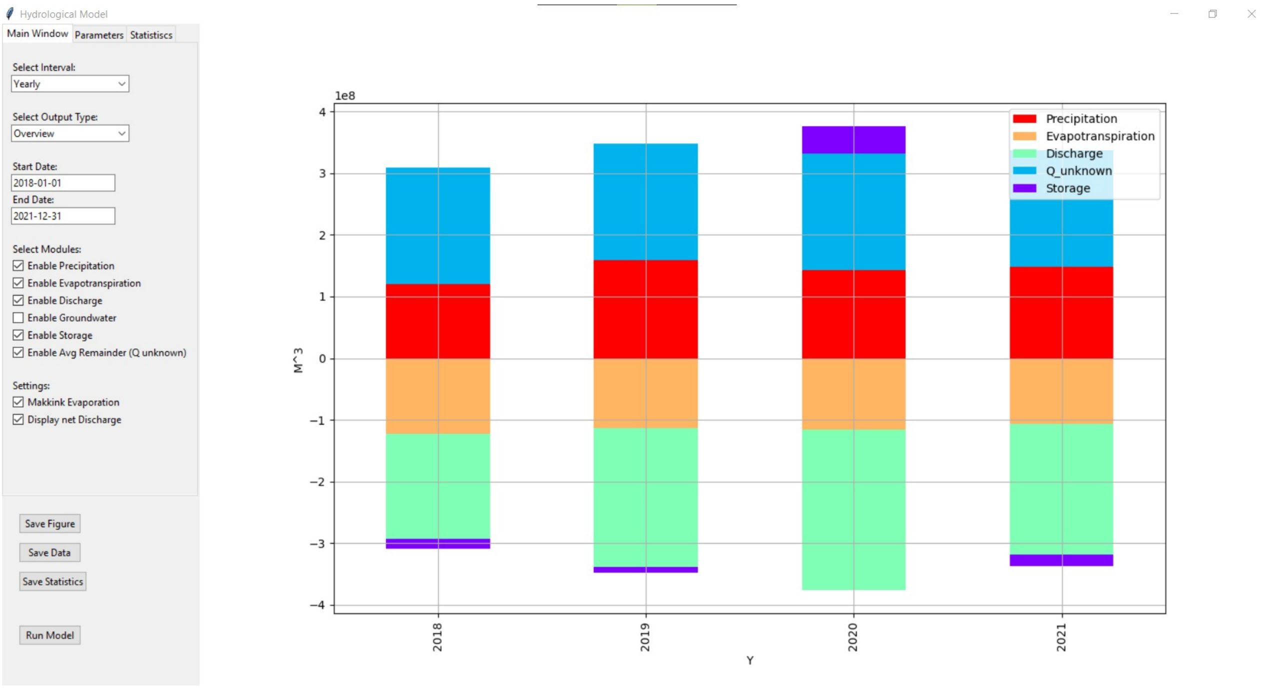
1. Main Window Tab. the tab with the most important settings for running the model. Here, the interval is selected, the output type and the time range. Also the modules and settings related to these modules can be found here.
2. Parameters Tab. Here, it is possible to tweak different parameters and factors which influence the model. This is mostly used for calibration purposes.
3. Statistics Tab. All the statistics generated by the model can be viewed here. The amount of statistics shown here are based on the input the user has given to the model, and can therefor differ per run.

On the lower part, 4 buttons are visible, which can be used to generate output:

1. Save Figure Button. The saving of figures is done by using the Save Figure button in the GUI. This saves the figure as a PNG file in the working directory of the model. This makes it possible to run the model several times and save the results in the meantime without having to exit the application.
2. Save Data Button. Data can be exported by using the data export button. When the button is pressed, the data which was used to create the graph which is visible in the GUI is saved to a CSV file. In this file, all the modules which have been active have their output appended in seperate columns, such that easy processing in external programs is possibile.
3. Save Statistics Button. Statistics can be saved to a CSV file by the Save Statistics Button. This makes it possible to quickly generate other filetypes like tables for corresponding figures.

4. Run Model Button The Run Model button can be seen as the most important button of the model, as it calls the main function of the model (model function). It is possible to change parameters and use the run button multiple times after each other, without having to exit the application.

The output result side of the model presents the user with a white screen when the model has not run yet, but refreshes every time the model is run. The output side of the model scales with the user window, and provides the clearest results when the model is used at maximum window resolution.



Select Interval: Yearly

Select Output Type: Overview

Start Date: 2018-01-01

End Date: 2021-12-31

Select Modules:
☑ Enable Precipitation
☑ Enable Evapotranspiration
☑ Enable Discharge
☐ Enable Groundwater
☑ Enable Storage
☑ Enable Avg Remainder (Q unknown)

Settings:
☑ Makkink Evaporation
☑ Display net Discharge

Figure 12: GUI of the model

5.1.4 Schematic of the final model

The whole story is clearly summarized in the schematic drawings of the model, figure 13. In this figure there is a clear distinction between what is visible to the user, and thus the user must provide itself (data etc), and the underlying model. Arrows indicate how certain elements of the model are connected.

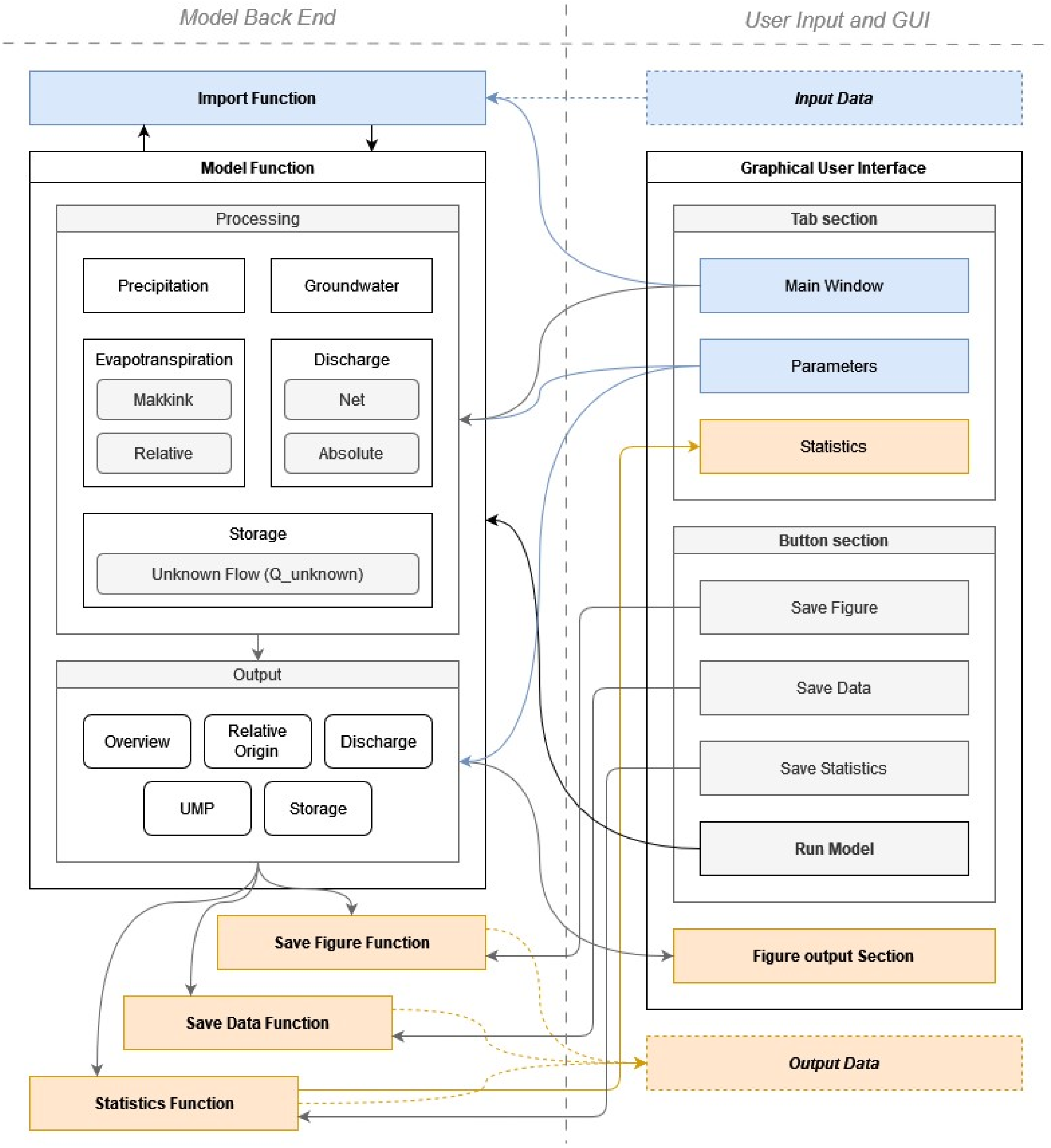


Figure 13: Schematic of the final Hydrological Water Balance Model

5.2 Model input

The model has a wide range of input options the user can change in the GUI. These can be categorized under several categories, as shown in table 8:

Name	**Type**	**Format**	**Usage**
Interval	Selection	List	Data selection
Output Type	Selection	List	Module selection
Start Date	Textbox	Date	Data selection
End Date	Textbox	Date	Data selection
Precipitation	Checkbox	Enabled/Disabled	Module selection
Evapotranspiration	Checkbox	Enabled/Disabled	Module selection
Discharge	Checkbox	Enabled/Disabled	Module selection
Groundwater	Checkbox	Enabled/Disabled	Module selection
Storage	Checkbox	Enabled/Disabled	Module selection
Unknown Flow	Checkbox	Enabled/Disabled	Module selection
Makkink Evaporation	Checkbox	Enabled/Disabled	Module Settings
Net Discharge	Checkbox	Enabled/Disabled	Module Settings
Precipitation Multiplication Factor	Parameter	Number range	Module Parameters
Evapotranspiration Multiplication Factor	Parameter	Number range	Module Parameters
Porosity	Parameter	Number range	Module Parameters
Factor TSM	Parameter	Number range	Module Parameters
Factor de Haandrik	Parameter	Number range	Module Parameters
Factor Afwateringskanaal	Parameter	Number range	Module Parameters
Factor Vecht Ommen	Parameter	Number range	Module Parameters

Table 8: User inputs in the GUI of the model

5.3 Model processing

The modules mentioned in section 5.1.2, which are used for the processing part of the model,have a certain way of translating data into water flows:

- Precipitation is determined by averaging three different monitoring stations located around the project area. This gives a reasonable determination of the amount of precipitation in millimetres. KNMI's measurement data are in 10 millimetres. By translating the measurement data into precipitation in metres, the amount of precipitation can be determined in the desired interval (in cubic metres) by multiplying it by the size of the project area. However, this method effectively omits runoff processes.

- Evapotranspiration data was determined by the KNMI by using solar radiation data. The actual amount of evapotranspiration by the Makkink method is provided by the KNMI in tenths of millimetres. In the same way as precipitation, the amount of evaporation can be determined by multiplying it times amount of square meters of the projectarea. An evaporation factor ensures that the amount of evaporation can be calibrated so that it fits the model results.

- Groundwater is calculated by determining the rises and falls of the groundwater level and adding them together depending on the desired interval. Multiplying this by the estimated porosity of the soil, and the size of the project area, surface to groundwater flows (and vice versa) are determined.
- The discharge data is provided in the average discharge per hour (in cubic metres per second), and can therefore be determined by multiplying this value by the amount of seconds there are in an hour (3600). From this quantity, it can be determined how much water flows through a given measurement point per the desired interval. These values can be displayed with separate in and out items, but can also be displayed as net values.
- Storage can be seen as the residual value of the water balance. assuming that all options for water in the water balance have already been approached, it can be assumed that the remainder is stored in surface and groundwater basins. Since this is obviously not...
- Unknown flow is used to calibrate the model. Since it can be assumed that the net amount of storage flow over a long time is around zero, due to the finite properties of water storage in the area. Hence the Unknown flow is introduced. This is the average surplus of flow which is not covered by one of the other processes. In the case where the unknown flow is zero, it can be assumed that the model is calibrated correctly.

5.4 Model output

As mentioned in section 5.1.2, the model can generate different types of output. This is done in the output section of the model. Here based on the user input 5 different types of output can be generated.

- "Overview" output is a stacked bar graph containing an overview of all items included in the calculation of the water balance. This is a common way of displaying water balances because seasonal influences are clearly visible.
- "Relative Origin"-output is a pie graph in which, based on the amount of water flowing from the measuring point Vecht Ommen, the origin is examined. Here the share of runoff and the other water flows can be viewed. This output works only at yearly intervals.
- "Discharge" shows with a line graph how much water flows through the measuring points. This data output can create up to day interval graphs, which allows it to be used to analyze discharge data.
- "UMP", also known as Unrealised Measuring Point, uses the input data to approximate a fictitious measuring point located between area 1 and area 3. This is done by approximating this measurement point from the area above it, by adding the amount of precipitation and evaporation occurring in the area to the amount of water flowing into the upper area. The down

approach is done by subtracting the amount of precipitation and evaporation, along with how much with water still flowing into the area in the lower area, from the amount which flows out of the area at Vecht Ommen. Theoretically, there should be no difference between this upper and lower approximation, if the water balance is closed.

- "Storage" can be used to generate graphs showing the storage. This is mainly to supplement the overview output.

5.5 Model portability

By using a python package called Py-installer, it is possible to run the model on every system with an operating system installed. Py-installer bundles the python code with the necessary packages and files into an executable file. This makes the model portable, and also makes it possible for everyone to gather the same results while on different systems. There is no need to have python installed on the pc to run the model, since the runtime is embedded into the executable. The executable does not need administrator/other forms of elevated rights when used.

6 Results: Water balance

In this section, the water balances which are output of the developed model, are discussed.

6.1 Uncalibrated results

For the uncalibrated data, as little as possible was deliberately done with the data loaded. Table 9 shows these initial parameters for the graphs that came out of this.

Input	Value
Start Date	2018-01-01
End Date	2021-12-31
Factor Precipitation	1.0
Factor Evapotranspiration	1.0
Porosity	0.40
Factor Inflow_Haandrik	1.0
Factor Inflow Afwateringskanaal	1.0
Factor Inflow TSM	1.0
Factor Outflow Vecht Ommen	1.0

Table 9: Parameters used for the uncalibrated results

This results in the following relative origin pie graph:

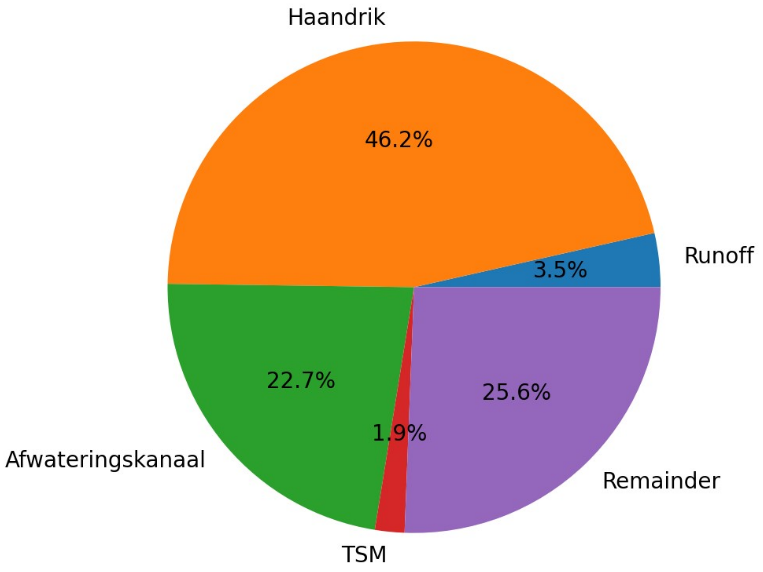


Figure 14: Relative origin graph when model is not calibrated

Runoff is the precipitation minus the evapotranspiration. These pie graph values do not fall in line with what would be expected from the values seen in table 7.

6.1.1 Waterbalance yearly

For water the upcoming balance graphs, positive values can be considered input, and negative values output of the system. The following graph was generated with the interval set on year, and with every module enabled.

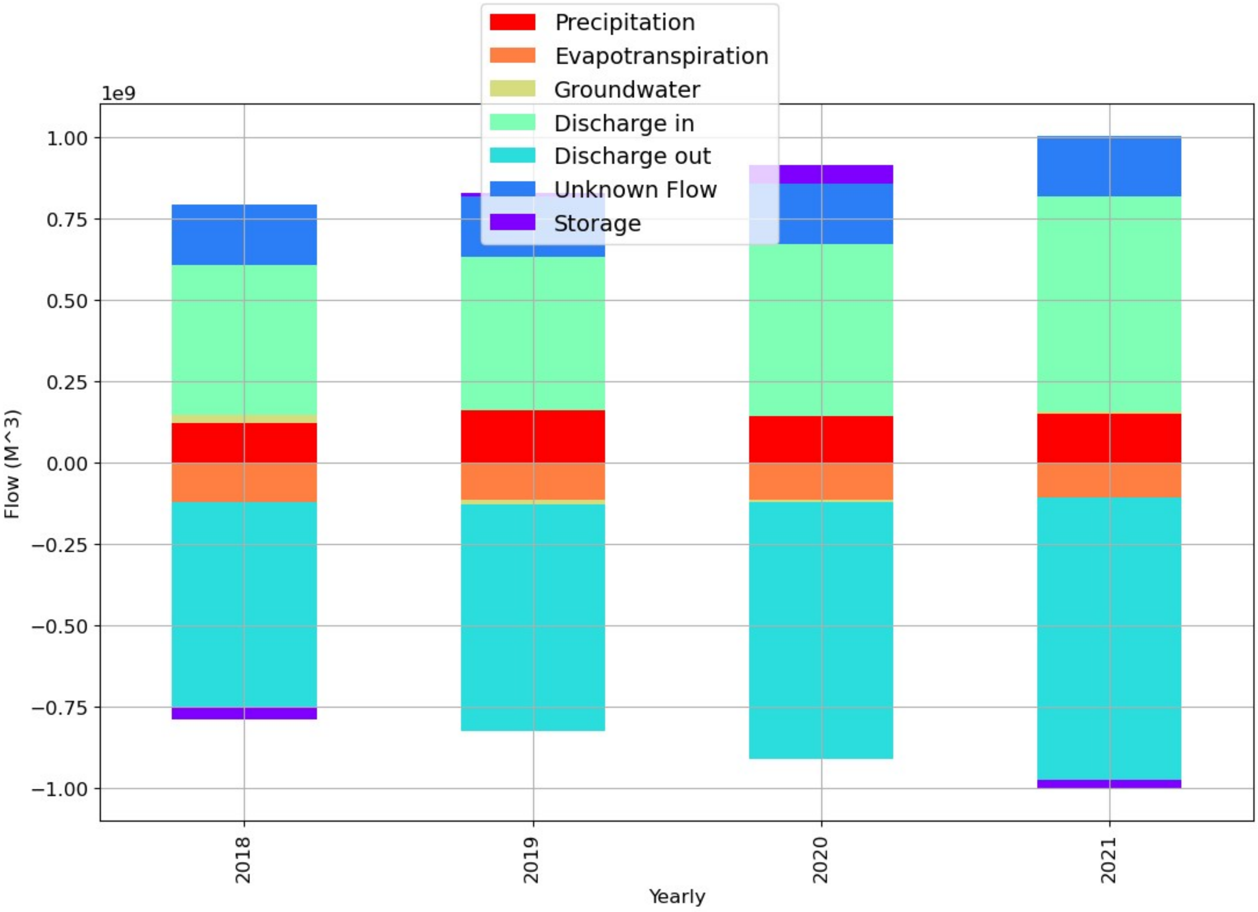


Figure 15: Water balance per year, uncalibrated

It can be stated that every year, the amount of discharge in the system tends to increase. It can be seen that only in 2018, groundwater has a visible influence on the water balance in the graph, with a surplus of water flowing into the ground (out). For other years, the groundwater flow is merely visible in the graph.

6.1.2 Waterbalance quarterly

The quarterly based water balance graphs use the following months for their quartiles:

Q1	January - March
Q2	April - June
Q3	July - September
Q4	October - December

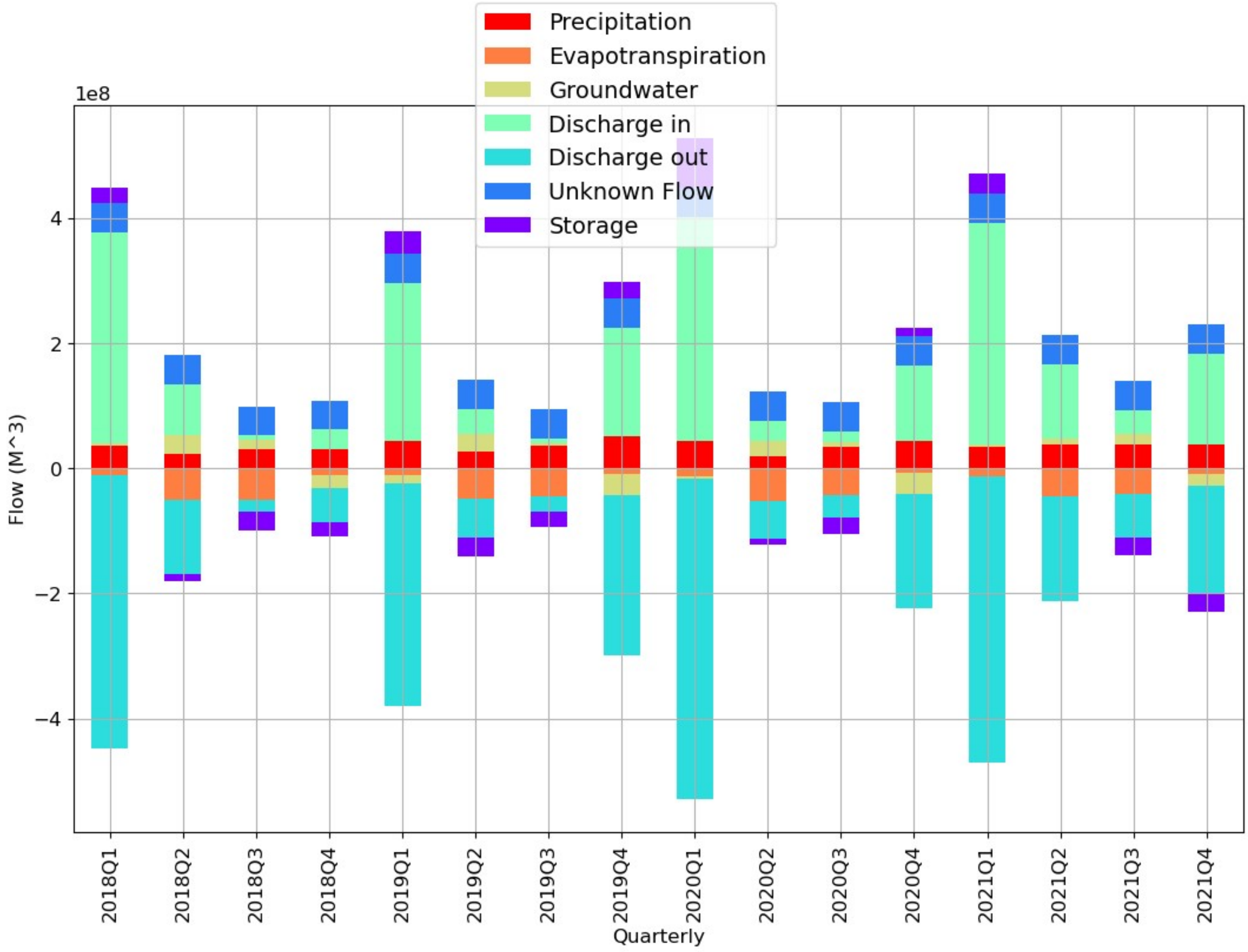


Figure 16: Water balance per quartile, uncalibrated

Seasonal effects are now visible, for example the increase in discharge around Q1. and the higher levels of evapotranspiration around Q2 and Q3.

Groundwater starts to play a bigger role when the resolution is increased, and follows a seasonal trend.

6.1.3 Waterbalance monthly

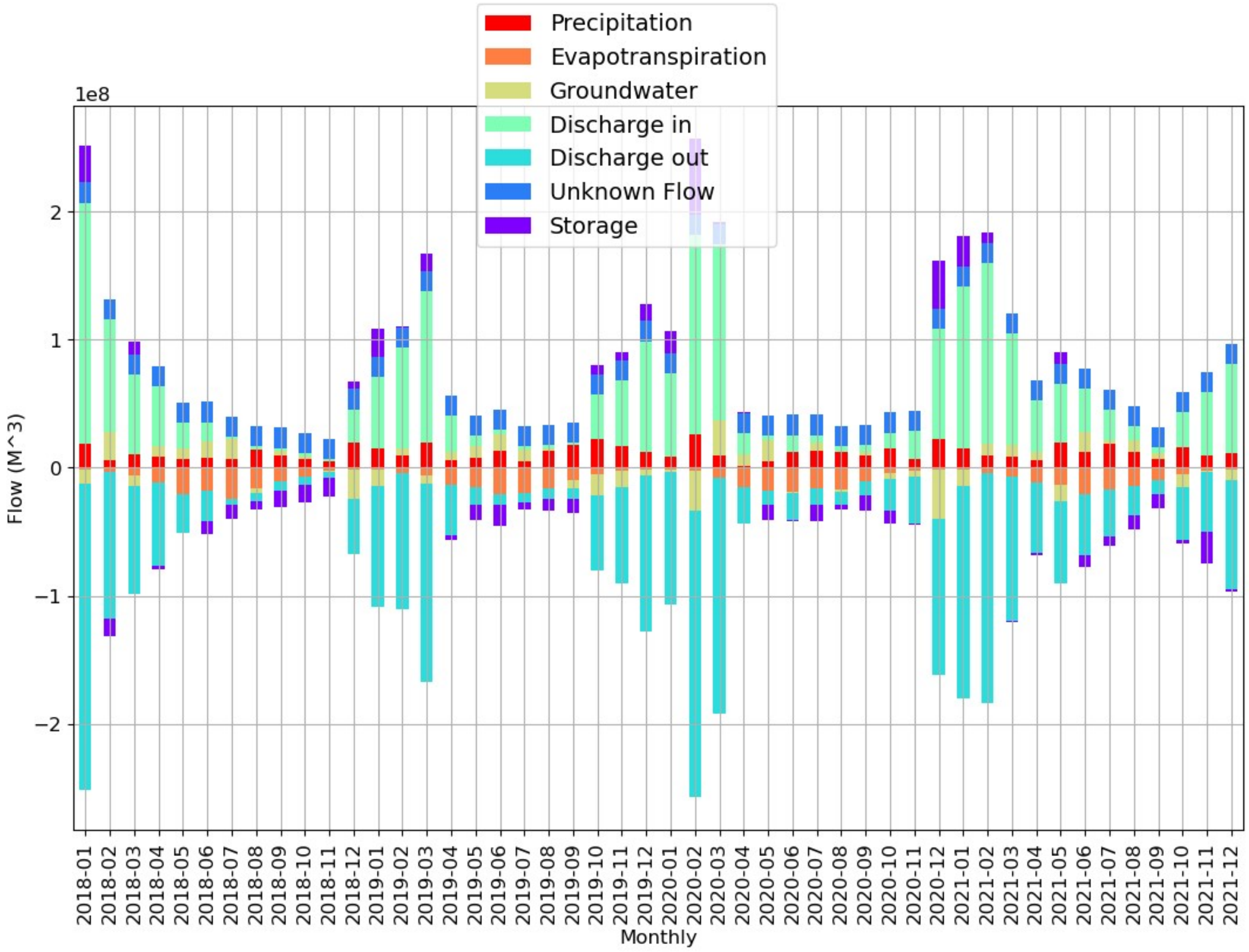


Figure 17: Water balance per month, uncalibrated

The uncalibrated waterbalances on monthly basis show the seasonal even better. Now, a clear fluctuating evapotranspiraton graph is visable, and distinct months with high discharge are visible in the graph. Groundwater now becomes a relatively high influence on the water balances.

6.2 Calibrated results

The calibrated graphs have been generated with the following parameters:

Input	Value
Start Date	2018-01-01
End Date	2021-12-31
Factor Precipitation	1.0
Factor Evapotranspiration	0.75
Factor Inflow_Haandrik	1.21
Factor Inflow Afwateringskanaal	0.76
Factor Inflow TSM	1.06
Factor Outflow Vecht Ommen	0.84

Table 10: Parameters used for the calibrated results

The time interval is the result of a data availability analysis. The parameters are obtained by adjusting parameters in the model until the results of the "Relative Origin"-graph matches table 7. The Evapotranspiration factor is an educated guess based on evapotranspiration literature of STOWA (Bos-Burgering et al., 2020).

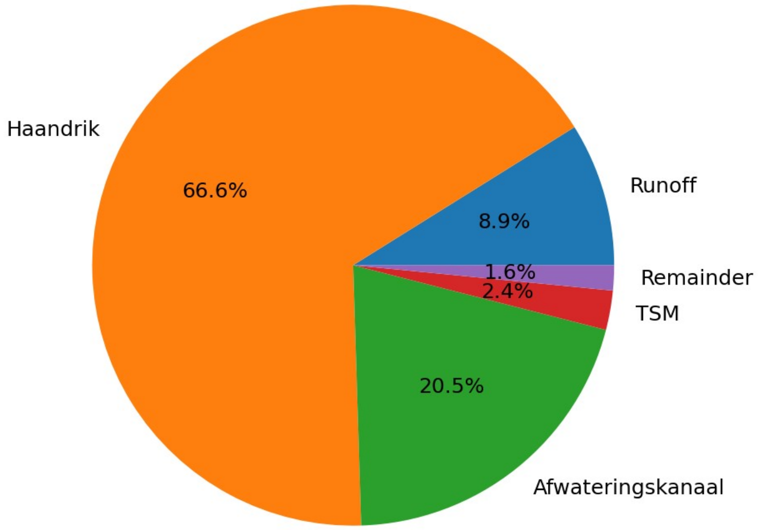


Figure 18: Relative Origin graph with calibrated model

Groundwater processes have been disabled in the model for the calibrated results.

6.2.1 Water balance yearly

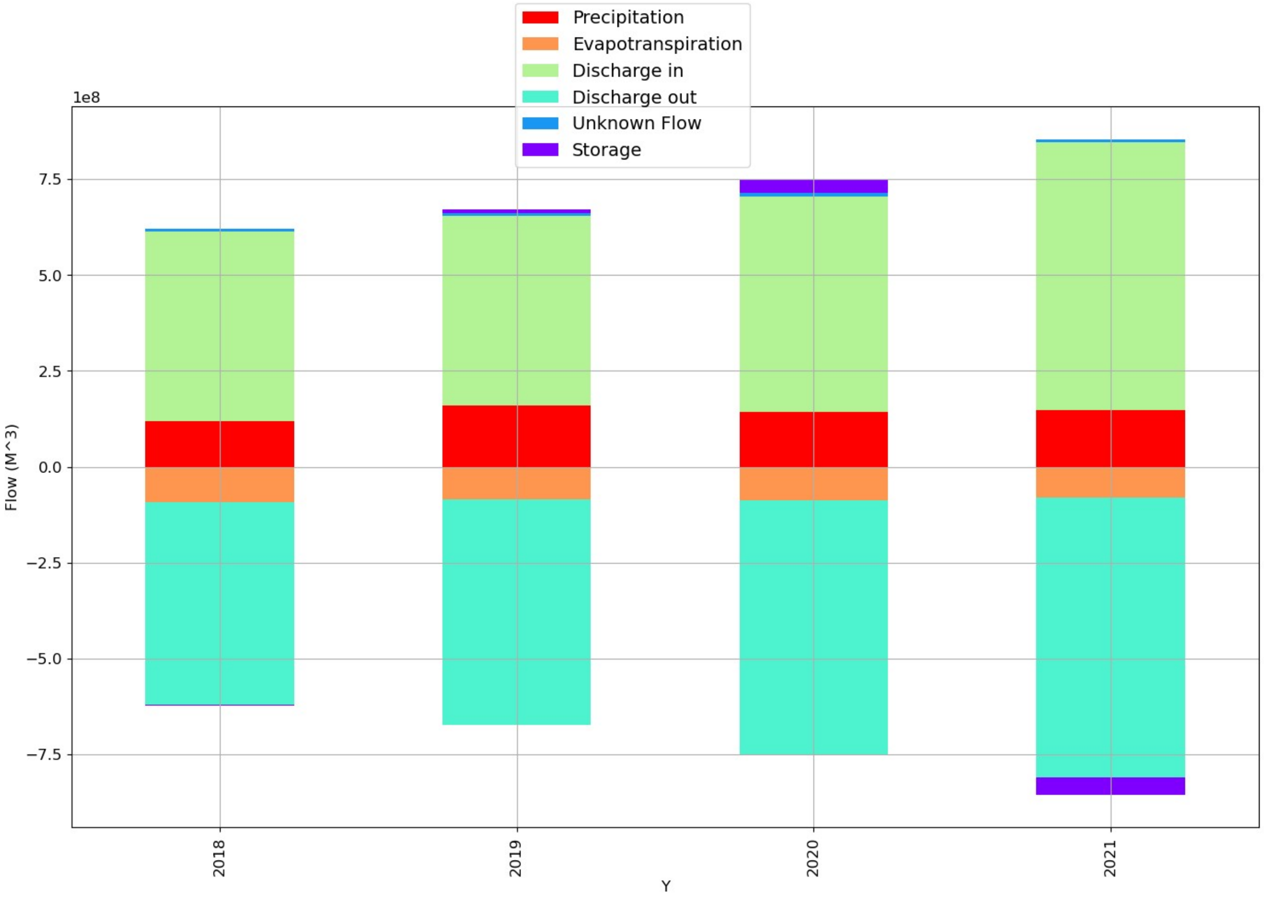


Figure 19: Water balance per year, calibrated

The calibrated year balances have a significant smaller amount of unknown flow and storage, which is expected when using calibrated values.

6.2.2 Water balance quarterly

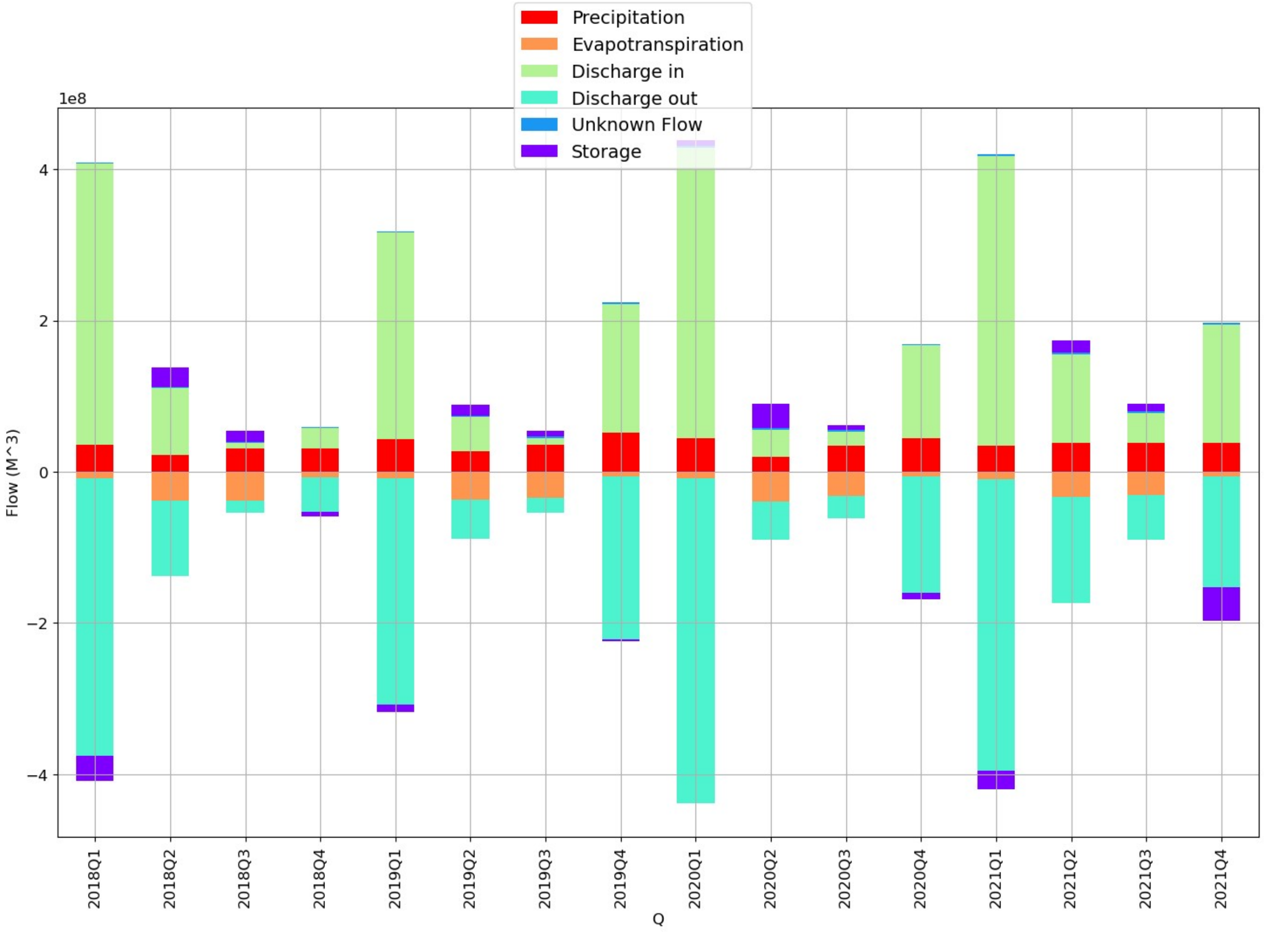


Figure 20: Water balance per quartile, calibrated

Again, quarterly calibrated water balances provide data which is expected: storage of water during the wet quartiles (Q1 and Q4) and the extraction of water from storage during the dry quartiles (Q2 and Q3). Furthermore is there almost no unknown flow in the system.

6.2.3 Water balance monthly

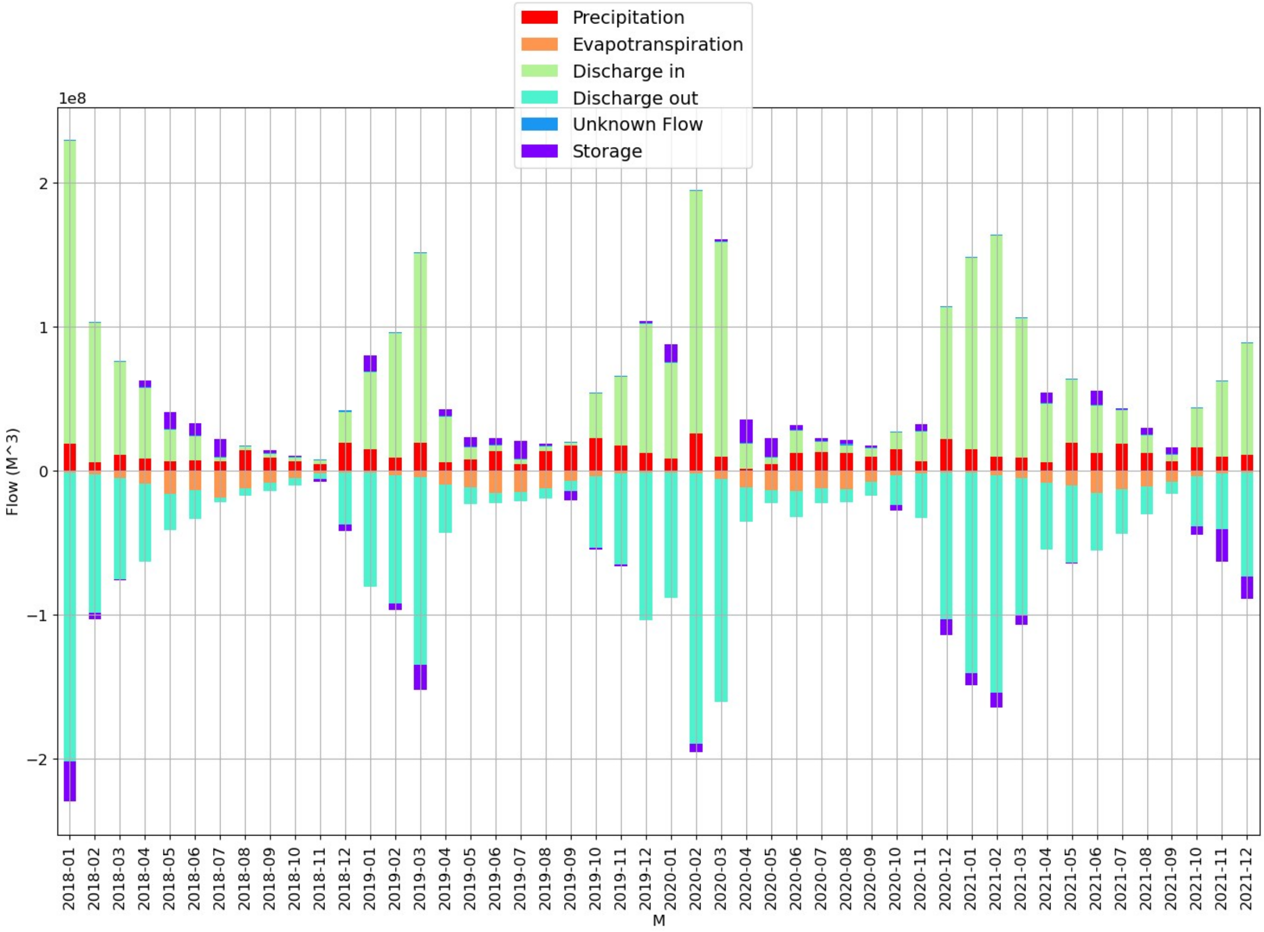


Figure 21: Water balance per month, calibrated

For the monthly water balances, some deviations are visible compared to the quarterly water balances. For some months, the addition to the storage is relatively high, while the next month, the retrieval from the storage area is visable. This indicates, based on literature (Bear, 1988) that possible surface water storage may be the case.

7 Results: Miscellaneous

7.1 Influence sewage treatment plants

Only one wastewater treatment plant operates in the area, namely RWZI Hardenberg. This draws its water from the area, and discharges it here as well. This is therefore a closed circle in the project area, so it has no impact on the water balance.
No other STPs operate around the perimeter of the area, so there are no unexpected inflows or outflows. RZWI Ommen, which operates close to the project area, discharges its water downstream into the Vecht, making it irrelevant to this area.

7.2 Fictional discharge unrealised measuring point

7.2.1 Uncalibrated

By using the values of table 9, which represent de model parameters in an uncalibrated state, the following graphs are achieved for the unrealised measuring point:

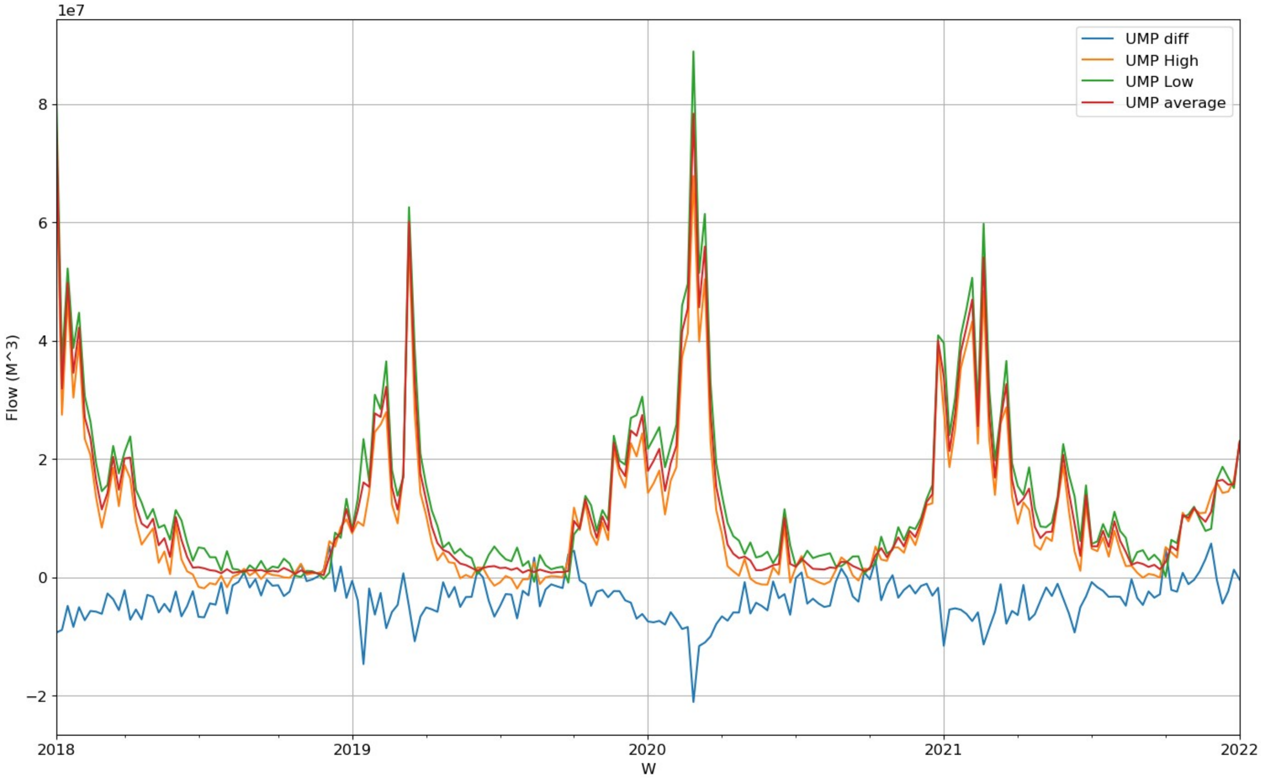


Figure 22: Unrealised measuring point, uncalibrated

The 'UMP-high' approximation, which approaches the measuring station from the top of the area is clearly smaller here than the 'UMP-low' approximation, with a few exceptions. Predominantly, the difference is smaller during the drier periods, indicating a relative difference between the two approaches.

The average difference between the high and low approach of the unrealised measuring point is around $0,362 \cdot 10^7\ m^3$.

7.2.2 Calibrated

After applying the parameters of table 10, which were achieved by calibrating according to the flow rates guide sheet (see appendix B.1), the following unrealised measuring point graphs were generated:

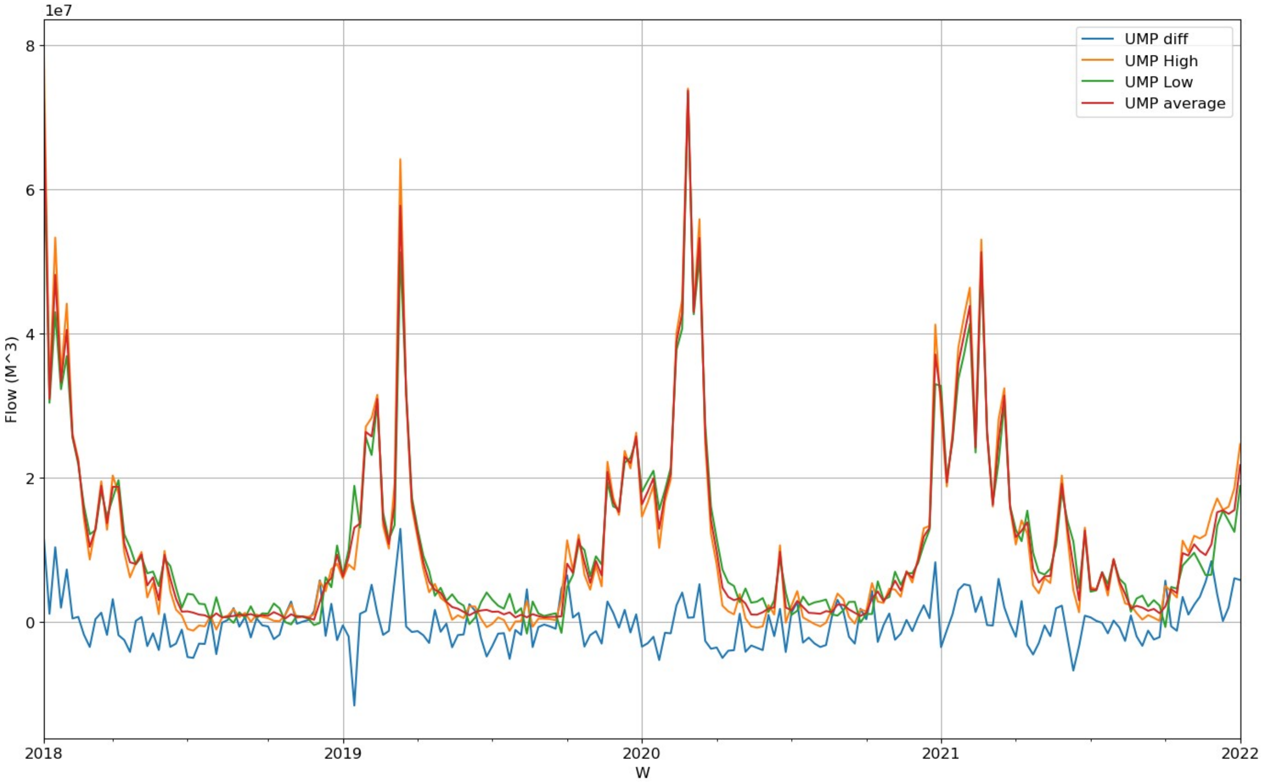


Figure 23: Unrealised measuring point, calibrated

Compared to figure 22, this graph has a difference which which seems to fluctuate more around the y = 0 value. There are still some differences visible between the two approximations, especially around the high discharge seasons. This still falls in line with the relative difference statement which was mentioned in section 7.2.1. The average differences between the two approaches is now around 96% lower with a value of $0,0157 \cdot 10^7\ m^3$.

7.3 Results field study

During the field survey, it was observed that seepage could potentially occur from the Almelo-De Haandrik canal. This may be partly due to the differences in height between the canal and the ditches around it. These ditches run alongside it for a large part of the canal. These ditches are mainly used for the agriculture that takes place around the canal. The height difference between the canal and these ditches is estimated at one and a half metres. The estimated average distance between the canal and the ditches is about 8 metres as the crow flies.
Few direct discharges were observed flowing directly from the canal into the project area. One of the few observed flows is the spillway that passes an estimated 7 litres per second in the Raderwijkerbeek near Hardenberg. Converted, this is 0.007 m^3/s.

Figure 24: Discharge from the Almelo-De Haandrik canal to the Radewijkerbeek (Photograph taken by author on 28-5-2023)

7.4 Seepage Almelo-de Haandrik canal

By using equation 6, the seepage from the canal to the surrounding ditches could be determined theoretically. The following values were found for this purpose:

Name	Value	Unit	Notes
k	0.001	cm/s	Permability factor
Δh	1.5	m	Head diference
L	8	m	Seepage length
D	2000	m	River length
S	5	m	Seepage crossection length

Table 11: Values used for seepage calculation

This results is the following equation:

$$0.01875 = \frac{0.001}{100} \cdot \frac{1.5}{8} \cdot 2000 \cdot 5 \tag{10}$$

A value of 0.01875 m^3/s was found.

8 Discussion

In the results it can be seen that very many differences can be seen between the uncalibrated and calibrated results. This is partly caused by one of the uncertainties briefly touched upon during the method. The monitoring stations may have a larger deviation than thought, making it appear that the water balances do not seem to close on an annual basis. This is especially easy to see when the discharge at monitoring station Ommen is reduced by a factor between 15 and 20%. The unknown flow is then heavily reduced. This phenomenon therefore falls in line with what was discussed in the method under the uncertainties, namely that the measuring station near ommen structurally measures 20 percent too high. Moreover, it also appears that more parameters need to be adjusted to make the relative origin graphs of the discharge match the design values provided by the water board. For example, the inflow at De Haandrik through the Vecht appears to need to be 21% higher, while the inflow from the Afwateringskanaal should be 24% lower in this case.

One of the more important comments is that the groundwater flows cannot be sufficiently approximated, and because of the low quality in data. Also, the simplification made based on theory is a major source of uncertainty. The whole process of saturated and unsaturated groundwater layer is completely left aside here. This suggests that there is a linear relationship between groundwater levels and the amount of water flowing in and out of the area. Of course, this is not necessarily the case. There is also a second problem with groundwater, which is potential evaporation. Because in the summer months a reasonable amount of water is pumped up by farmers (van der Meer, 2018), and water also evaporates from the unsaturated soil layer, this method may approach a water flow twice. Namely via approximating evaporation via solar radiation with the Makkink Method, and via the change in groundwater levels. The Makkink Method seems more reliable here, because it is actually confirmed by sufficient literature and field studies. It was therefore decided to disable the groundwater module in the model by default. Another benefit from this is that it also leads to faster model run times.

For evaporation, it was decided not to use the crop factors, and to use a single evaporation factor for the entire system. This was done primarily because the BRP crop data used to determine crop use proved difficult to link to the crop factors themselves. This requires too much work, as the BRP shows that for each year the crops change. This would mean having to manually link crop factors to land use for 5 different years, and potentially applying them incorrectly. Finally, applying crop factors may have too little impact on the final result because of the greater uncertainty in other types of water flows in the area. A single evaporation factor, and the use of rules of thumb by the water board may therefore be a suitable alternative solution

Precipitation may be approximated quite correctly in the current way. Because of the way the current areas are determined based on runoff boundaries, the possibility that the actual amount of precipitation is greater than the measured precipitation is small. Since the measurement data is actually coming from a location outside of the project area, it is more likely that the actual amount of precipitation is actually lower than anticipated, due to meteorological conditions.

Seepage calculation and other forms of discharge from the Almelo-de Haandrik canal are highly uncertain results. The water seepage from the almelo-de haandrik canal which happens in practice is hard difficult to determine, due to many factors that cannot be clearly estimated. Among other things, the permeability of the soil (the porosity factor k spoken of) can be a factor of 10 higher for the type of soil in question, fine sand. Also, it could not be clearly determined over what surface area water flows away from the canal into the project area, and it cannot be said with any certainty at all that this water actually enters the discharge system. The distances of the two water flows (the canal and the adjacent ditch), both horizontal and vertical are estimates, and therefore again represent an additional uncertainty in the calculation.

Calibrating the data proved to be much needed, as the unprocessed data by itself proved insufficient to generate suitable results. To this end, literature and reports were used to see how the model could be calibrated.
Validation proved to be a lot more difficult than model calibration. It proved difficult in practice to validate data. This was to some extent already predicted in the method, mainly because of the absence of multiple data sources. In the method, the possibility of using the [table] for validation was set up, however, it was already used to calibrate the model itself before validation. However, the possibility of using the unrealized measurement point is still open in the future. This should be able to provide further insights. Also, using the results generated by the model, conclusions can be drawn that can help with later validation of the model and data. Consider here certain issues that require more attention due to large uncertainties.

9 Conclusion

In this section the answers to the three research questions (and sub-questions) are provided, based on the results of the research.

1. Which features and processes are incorporated into the the developed water balance model?

   The following features are implemented into the model, based on the results of section 5:

   - Import function to import csv and text data in a wide range of formats.
   - Precipitation calculation based on collection station data.
   - Evapotranspiration calculation, by makkink or relative to precipitation.
   - Groundwater flow calculation based on groundwater levels.
   - Discharge calculation within the area from the 4 measuring points.
   - Storage estimation based on the remainder of the water balances.
   - Unknown flow, which represents average deviation in storage, and can be used for calibration.
   - Unrealised Measuring Point determination by using imported data for calibration and future validation purposes.
   - Graphical User interface for user calibration and operation.
   - Overview output graph for water balance display.
   - Relative Origin graph for calibration and informational purposes.
   - Storage graph, to get a better view into the changes in storage.
   - Discharge Graph for data analysis and informational purposes.
   - Export functions for data, figures, and statistics.

   More details of these functions can be found in section 5, which dives deeper into the resulting model which came out of this research.

2. To which extend can the water balance be closed with the developed water balance model?

   The water balance can be closed to some extend: It can be closed by calibrating the values. Unfortunately, there is no way to determine if these values are valid.

   (a) What are the biggest hydrological processes in the area?

   Discharge is the biggest hydrological process in the area, with next up precipitation and evapotranspiration. This is based on results achieved from general water balance plots in section 6.2.

   (b) Which processes generate uncertaincy within the water balance?

   Looking at the problems that already exist with the Vecht Ommen monitoring point, it can be seen that discharge is surely one of the biggest sources of uncertainty. Especially since the flow of water is a large item in the water balance, which was found in Research Question 2a, a small deviation in a few percent can already cause a big problem about the certainty of the results. The After discharge, evaporation represents a lot of uncertainty, partly because this is largely done as estimation in practice (Bos-Burgering et al., 2020), but also due to the way the Makkink evaporation formula assumes perfect circumstances for the calculation.

(c) What is the most detailed resolution in which the model still gives sufficient results?
The model is able to provide water balances up to the monthly interval. With a weekly interval, the model does not provide usable results for water balances. For other figures like discharge analysis or the Unknown Measurement Point plots, it is possible to maintain a daily interval for the output.

3. How does the model support the water board in their operational water management?
The model is able to produce a good presentation of the data, and the data can be manipulated by factors easily. The process of calibrating can be easily done by a GUI, but the loading of data is something which still requires python knowledge. A couple of sidefunction's are implemented. Looking at the output research question 1, the following features from the feature list are implemented to comply with the needs of the water board:

   - Import function to import csv and text data in a wide range of formats.
   - Unrealised Measuring Point determination by using imported data for calibration and future validation purposes.
   - Graphical User interface for user calibration and operation.
   - Relative Origin graph for calibration and informational purposes.
   - Discharge Graph for data analysis and informational purposes.
   - Export functions for data, figures, and statistics.

   Therefor, it can be concluded that the model supports the operational water management of the water board Vechtstromen in multiple ways.

It can be concluded that the research aim, determining how feasible it is to establish water balances in the managerial area of the Vechstromen Water Board, has been achieved. All research questions have been answered, and it can be said that it is feasible to draw up water balances within the boundaries, but with some remarks, which have been addressed in the discussion.

10 Recommendations

In this chapter, the recommendations for the Vechtstromen water board are discussed. These recommendations should be considered before continuing the research on water balances in this area.

- Before the water board would get involved in setting up water balances for other sub-areas, it should check when measuring points were last calibrated. This research has shown that especially in areas with a high throughput of water (in this case the Overijsselse Vecht), problems arise if one of the measuring stations has a structural deviation. After calibrating these measuring points, it is possible to retry to recreate these water balances. From these correct water balances, a better picture can also be obtained more quickly of whether measuring stations are starting to deviate from the expected values.
- Due to a lack of information and understanding about groundwater processes in this area, it is difficult to get a good picture of water storage. The biggest issues at play in this area are drought-related, making a lack of understanding of one of the main storage sites quite problematic. A better understanding of groundwater, and for example a list of groundwater abstractions, may well help with an understanding on this item.
- Ultimately, it would be very practical to be able to use the model in Waterschap Vechtstromen' current modelling environment. This is possible by, for example, looking at the REST integration that Delft-FEWS (and, in this case, the Vechtstromen implementation of it, FEWS-Vecht) has on board. This makes it possible to request data for the model via an API, such as a clear insight into precipitation in the area, or the use of real-time groundwater levels. Thus, instead of being reactive, it may be possible to respond adaptively to certain situations. (Deltares, 2013)
- Possible additional features for the water balance model:
  - Configuration file where certain default settings can be adjusted
  - Automatically detect data type and start of collumns in dataset when importing
  - Possibility to add datasets by importing them in the GUI (and managing them there)

Glossary

Delft-FEWS Modular framework model developed by Deltares.

FEWS-Vecht Derivative of Delft-FEWS made for Vechtstromen waterboard by Deltares.

Flask Popular Python web framework used for building web applications. It is lightweight, flexible, and easy to use, making it a popular choice for developing APIs and small to medium-sized web applications. Flask provides a set of tools and libraries for handling web requests and responses, rendering templates, and working with databases.

Hoogheemraadschap Synonym of Waterschap.

KNMI Koninklijk Nederlands Meteorologisch Instituut, translates to Royal Dutch Meteorological Institute.

Pandas Popular open-source Python library used for data manipulation and analysis. It provides data structures for efficiently storing and manipulating large datasets, as well as tools for data cleaning, reshaping, and visualization. Pandas is widely used in data science and machine learning applications for tasks such as data preprocessing, feature engineering, and data exploration.

TKinter Standard Python library for creating graphical user interfaces (GUI's) that allows developers to create windows, buttons, menus, text boxes, and other GUI elements.

Waterschap Water board.

References

Bear, J. (1988). *Dynamics of fluids in porous media*. Dover. https://books.google.nl/books?id=lurrmlFGhTEC

Bijlsma, A. (2022). *Debietmetingen Overijsselse Vecht (Concept version)*.

Bos-Burgering, L., Weerts, A., Pouwels, J., Jacobs, C., & Jansen, F. (2020). Deltafact verdamping. https://www.stowa.nl/deltafacts/zoetwatervoorziening/droogte/verdamping

Das, B., & Sobhan, K. (2014). *Principles of geotechnical engineering, si edition*. Cengage Learning. https://books.google.nl/books?id=L925CgAAQBAJ

de Bruin, H. (1981). The determination of (reference crop) evapotranspiration from routine weather data. *28*, 25–37.

Deltares. (2013). Delft-FEWS POST & REST examples. https://publicwiki.deltares.nl/display/FEWSDOC/FEWS+PI-JSON+REST+Examples

Deltares. (2021). *Definitief eindrapport verdiepend schade-onderzoek Kanaal Almelo – De Haandrik* (11207155-011-GEO-0001). https://overijssel.notubiz.nl/document/10560426/4

de Ridder, N., & Boonstra, J. (1994). Analysis of water balances. In H. Ritzema (Ed.), *Drainage principles and applications* (pp. 601–633). ILRI Wageningen. https://edepot.wur.nl/262058

Dooge, J. C. I. (1968). The hydrologic cycle as a closed system. *International Association of Scientific Hydrology. Bulletin*, *13*(1), 58–68. https://doi.org/10.1080/02626666809493568

Doorenbos, J., & Pruitt, W. (1977). Crop water requirementss. *FAO Irrigation and Drainage Paper*, *24*, 144.

Eden, J. M., Kew, S. F., Bellprat, O., Lenderink, G., Manola, I., Omrani, H., & van Oldenborgh, G. J. (2018). Extreme precipitation in the netherlands: An event attribution case study. *Weather and Climate Extremes*, *21*, 90–101. https://doi.org/https://doi.org/10.1016/j.wace.2018.07.003

Elbers, J., Moors, E., & Jacobs, C. (2010). Gemeten actuele verdamping voor twaalf locaties in nederland. https://edepot.wur.nl/136999

European Commission. (2015). *Guidance document on the application of water balances for supporting the implementation of the wfd: Final: Version 6.1 – 18/05/2015.* Publications Office. https://doi.org/10.2779/352735

Feddes, R. (1987). *Crop factors in relation to makking reference-crop evapotranspiration*. Institute for Land; Water Management Research. https://books.google.nl/books?id=C2MXMgAACAAJ

Gulliver, J., Erickson, A., & Weiss, P. (2010). Evaporation and evapotranspiration. https://stormwaterbook.safl.umn.edu/water-budget-measurement/evaporation-and-evapotranspiration

Harbers, M. (2022). *Brief van de minister van infrastructuur en waterstaat*. Ministerie van Infrastructuur en Waterstaat. https://zoek.officielebekendmakingen.nl/kst-32698-64.html

Hevner, A. R. (2007). A three cycle view of design science research. *Scandinavian journal of information systems*, *19*(2), 4.

Hoogeveen, M., van Bommel, K., & Cotteleer, G. (2003). *Beregening in land- en tuinbouw; rapport voor de droogtestudie nederland*. LEI.

IPCC. (2022). *Climate change 2022: Mitigation of climate change. contribution of working group iii to the sixth assessment report of the intergovernmental panel on climate change* (P. Shukla,

J. Skea, R. Slade, A. A. Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, & J. Malley, Eds.). Cambridge University Press. https://doi.org/10.1017/9781009157926

Kraak, H. (2020). Een bed op klosjes, zó scheef is de vloer. *Volkskrant*. https://www.volkskrant.nl/nieuws-achtergrond/een-bed-op-klosjes-zo-scheef-is-de-vloer~b065f215/

Makkink, G. (1957). Testing the penman formula by means of lysimeters. *J. Inst. Water Eng.*, *11*.

Olsthoorn, T. N. (1977). In nederlandse zandformaties zijn het doorstroomde en het totale porievolume aan elkaar gelijk. *H2O*, *5*, 118–122. https://edepot.wur.nl/401072

Penman, H. L. (1948). Natural evaporation from open water, bare soil and grass. *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences*, *193*(1032), 120–145. Retrieved June 7, 2023, from http://www.jstor.org/stable/98151

Perrault, P. (1674). De l'origine des fontaines. https://archive.org/details/deloriginedesfon00perr

Simon, H. A. (1970). *Sciences of the artificial*. MIT Press.

Simon, H. A. (1988). The science of design: Creating the artificial. *Design Issues*, *4*(1/2), 67–82. Retrieved July 2, 2023, from http://www.jstor.org/stable/1511391

Sutcliffe, J. V. (2004). *Hydrology: A question of balance*. IAHS Press.

van der Meer, R. (2018). *Watergebruik in de land- en tuinbouw, 2015-2016*. Wageningen University; Research. https://edepot.wur.nl/463716

van Buren, W., Kramer, P., de Crook, R., & Menkveld, A. (2008). *Een pilotstudie naar de haalbaarheid van het opstellen van deelgebieds-waterbalansen: Toepassing van de methodiek op de data van 2005*. Hoogheemraadschap De Stichtste Rijnlanden. https://edepot.wur.nl/10812

Vicente-Serrano, S. M., Beguería, S., & López-Moreno, J. I. (2010). A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. *Journal of Climate*, *23*(7), 1696–1718. https://doi.org/10.1175/2009jcli2909.1

Wang, C.-y., & Manga, M. (2021). Groundwater flow and transport. https://doi.org/10.1007/978-3-030-64308-9_2

Wanniarachchi, S., & Sarukkalige, R. (2022). A review on evapotranspiration estimation in agricultural water management: Past, present, and future. *Hydrology*, *9*(7), 123. https://doi.org/10.3390/hydrology9070123

A Maps

A.1 Area North

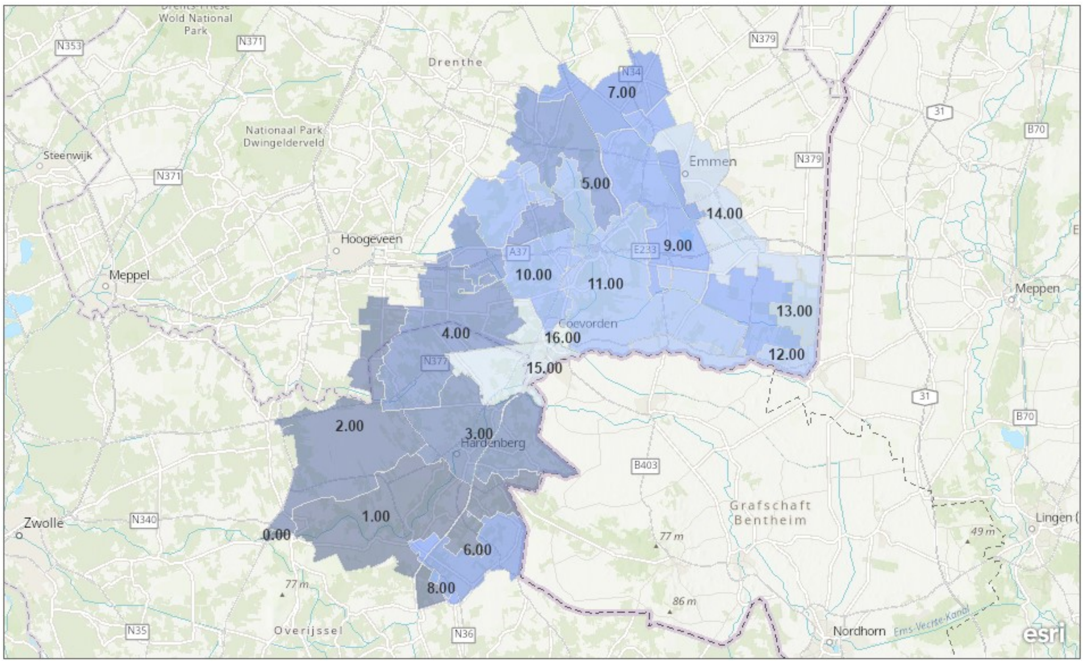


Figure 25: Northern area with sub-catchments

A.2 Area South

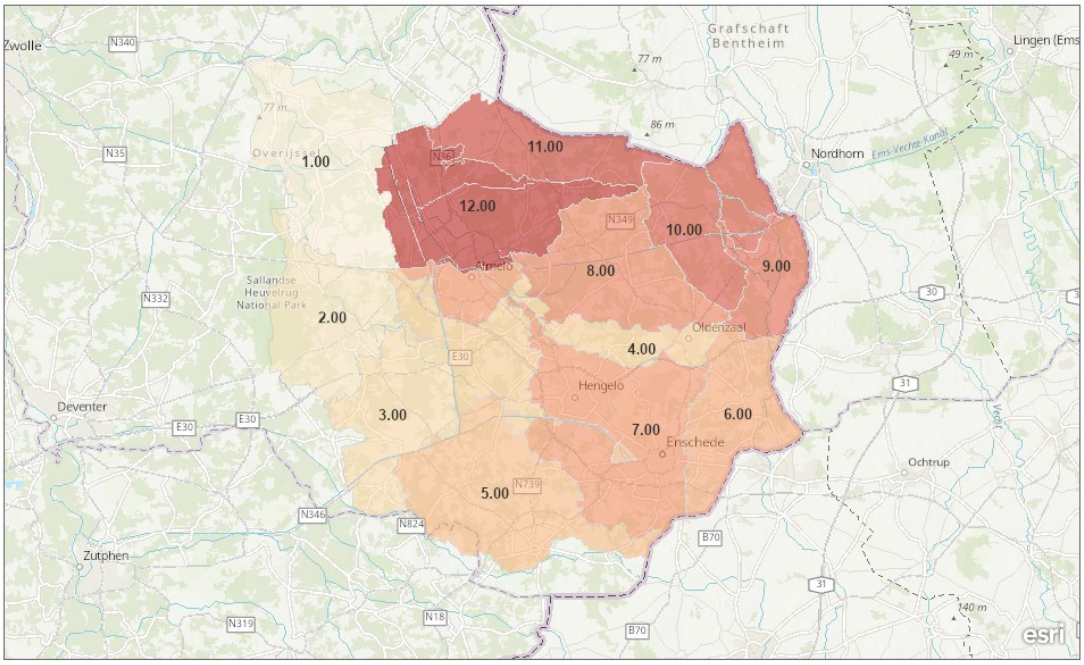


Figure 26: Southern area with sub-catchments

A.3 Larger scaled map managerial area

Figure 27: Water board vechtstromen map with larger scale

A.4 Land use

The following land use map has been used to gather information about the study area, especially for evapotranspiration related matters.

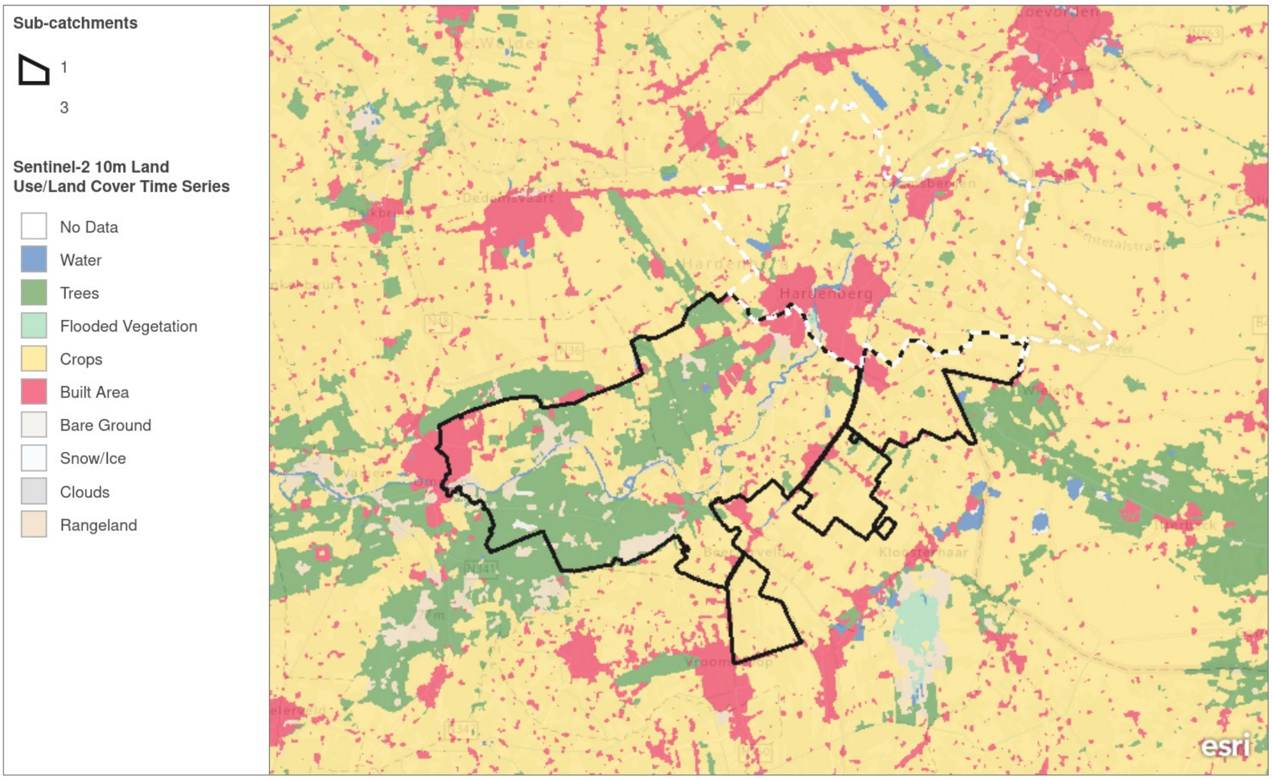


Figure 28: Sentinel-2 10m Land use map of the catchments

Retrieved from https://env1.arcgis.com/arcgis/rest/services/Sentinel2_10m_LandCover/ImageServer

B Tables

B.1 Flow rates guide sheet

This guidance sheet was provided to determine if the amount of water which is measured in at the measuring points falls in the same order of magnitude as what would be expected.

Lateraal	**1/100Q**	**1/4Q**	**1/2Q**	**T=1**	**T=10**	**T=25**	**T=100**	**T=200**
Emlichheim	0,5	23,0	52	101	157	177	207	222
De Haandrik	**0,5**	**23,2**	**53**	**102**	**159**	**179**	**209**	**224**
OV_2.3_R_Coevorden-Vecht-Kanaal	0,0	0,0	0	0	0	0	0	0
OV_2.3_L_Kanaal-Almelo-De-Haandrik	0,0	0,0	0	0	0	0	0	0
AK_C_Drentse-stuw	0,1	6,4	15	30	39	44	55	60
DM Ane Gramsbergen	**0,1**	**7,0**	**16**	**32**	**41**	**46**	**57**	**62**
OV_6.9_L_Gemaal_Willem-Snel	0,0	0,3	1	1	1	1	1	1
OV_10.8_L_Gemaal_Baalder	0,0	0,1	0	1	0	0	1	1
OV_12.8_R_Gemaal_Molengoot	0,0	0,4	1	2	2	2	2	2
OV_13.0_L_Beek_Radewijkerbeek	0,0	0,9	2	4	7	8	10	11
OV_14.1_L_Beek_Bruchterbeek	0,0	0,2	1	1	2	2	2	3
OV_15.7_L_Waterloop_Veenlandweg	0,0	0,0	0	0	0	0	0	0
OV_18.2_L_Beek_Oude-Vaart	0,0	0,3	1	2	2	2	2	2
OV_20.4_L_Beek_Marienberg-Vechtkanaal	**0,0**	**0,9**	**2**	**3**	**5**	**6**	**7**	**8**
OV_22.5_R_Waterloop_Rhezerwaterleiding	0,0	0,4	1	1	1	1	1	1
OV_27.5_R_Waterloop_Stegerdijk	0,0	0,3	0	1	1	1	1	1
OV_28.2_R_Waterloop_Arriervlier	0,0	0,3	0	1	1	1	1	1
OV_32.2_R_Waterloop_Galgengraven	0,0	0,3	0	1	1	1	1	2
Ommen Hesselmulertbrug	**0,6**	**35,0**	**79**	**152**	**224**	**252**	**298**	**322**
OV_34.6_R_Beek_Ommerkanaal	0,0	3,3	8	13	16	19	24	25
OV_35.6_L_Beek_Regge-Linderb.-Hamw.	1,6	13,8	26	48	66	79	97	103

Table 12: Flow rates expected at design situations

Meaning of columns:

- 1/100Q = summer discharge reached or exceeded 95% of the year
- 1/4Q = winter discharge reached or exceeded 80 days per year
- 1/2Q is reached or exceeded 15 days per year
- T=... once every ... years

B.2 Relative values flow rates guide sheet

The guide sheet values in section B.1 can be converted to relative values, by looking at them relatively to what flows out of the system at the Vecht in Ommen (hesselmulert bridge). Three scenarios were chosen from the table to form a good average. 1/4Q, 1/2Q and T=1 values were chosen because these are values valid for an average year. The T=10 and the 1/100Q values were already found to be relatively different from the other values. Therefore, these were not included.

Table 13 shows the measuring points relative to the measuring point Vecht Ommen (hesselmulert bridge), and the average of the three columns:

Measuring Point	**1/4Q**	**1/2Q**	**T=1**	**Average**
De Haandrik	0.662857	0.67088608	0.671053	0.66826528
DM Ane Gramsbergen (Afwateringskanaal)	0.2	0.20253165	0.210526	0.20435265
Marienberg-Vechtkanaal (TSM)	0.025714	0.02531646	0.019737	0.02358919
Remainder	0.111429	0.10126582	0.098684	0.10379287

Table 13: Inflow measuring points relative to the measuring point Vecht Ommen

B.3 k-Values for different soil types

Soil Type	k (cm/sec)
Clean Gravel	100-1.0
Coarse Sand	1.0-0.01
Fine Sand	0.01-0.001
Silty Clay	0.001-0.0001
Clay	<0.000001

Table 14: Typical values of Hydraulic Conductivity of Saturated Soil (Das and Sobhan, 2014)

C Additional results model

C.1 Calibrated net discharge overview

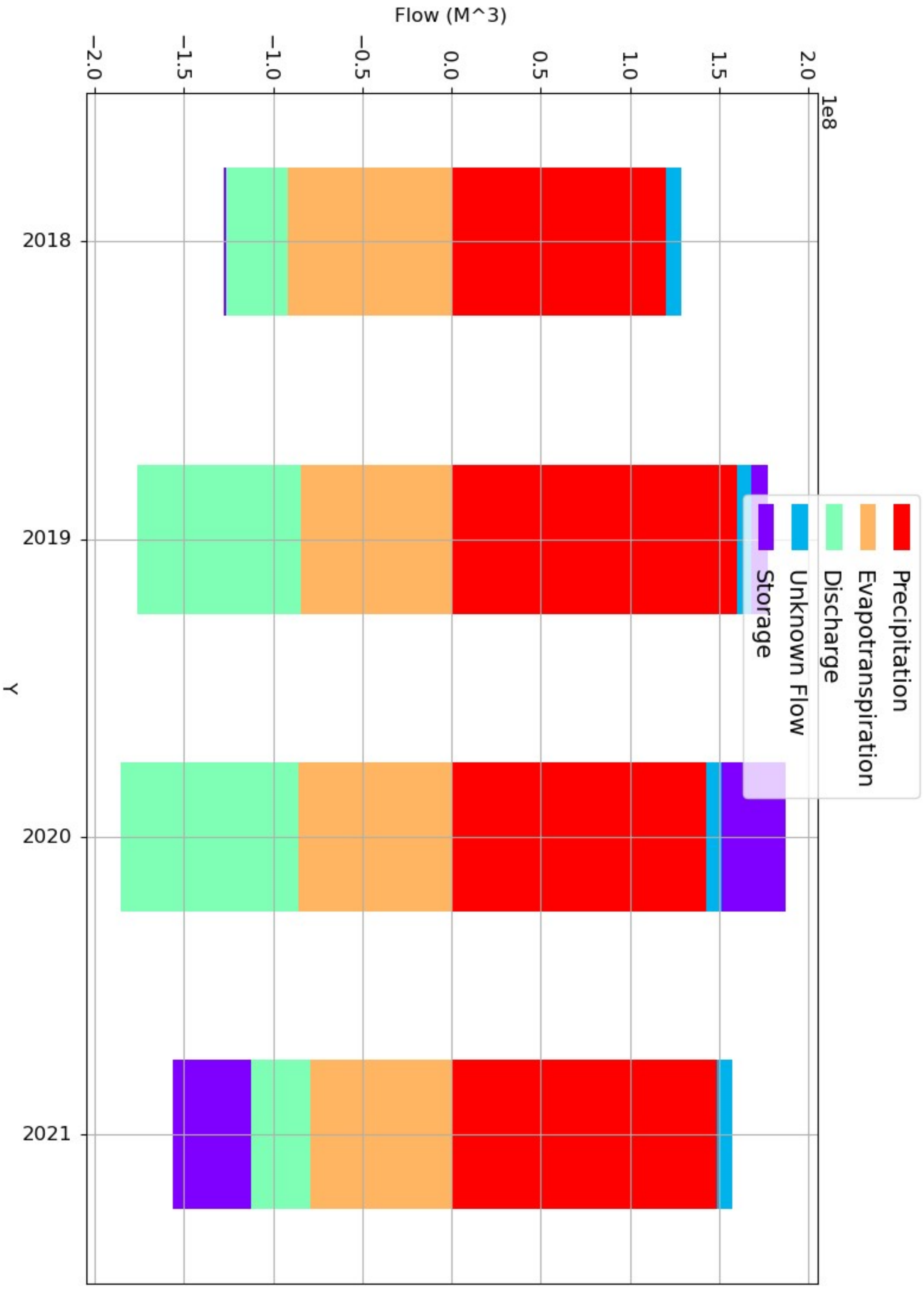


Figure 29: Net Discharge Overview graph year

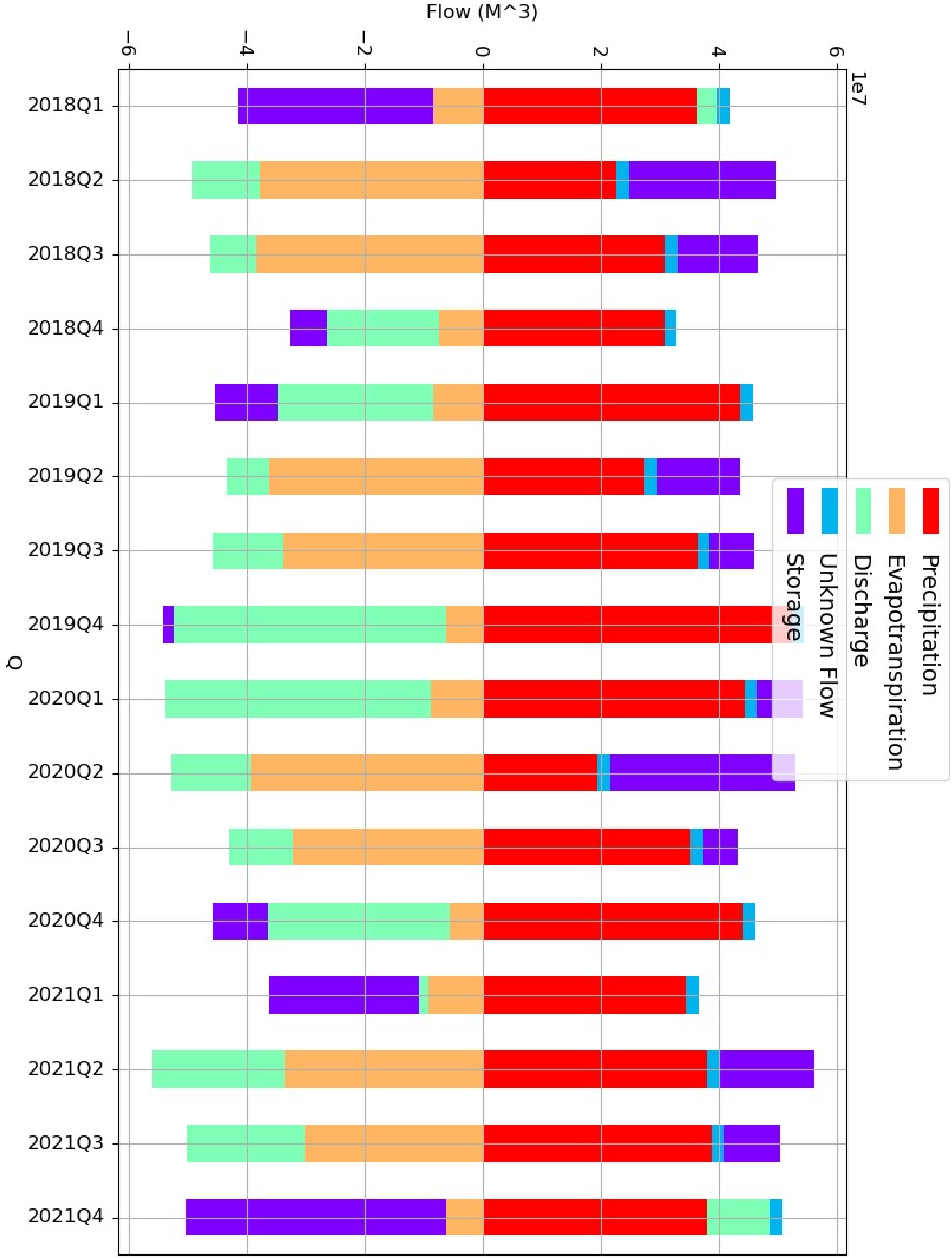


Figure 30: Net Discharge Overview graph Quartile

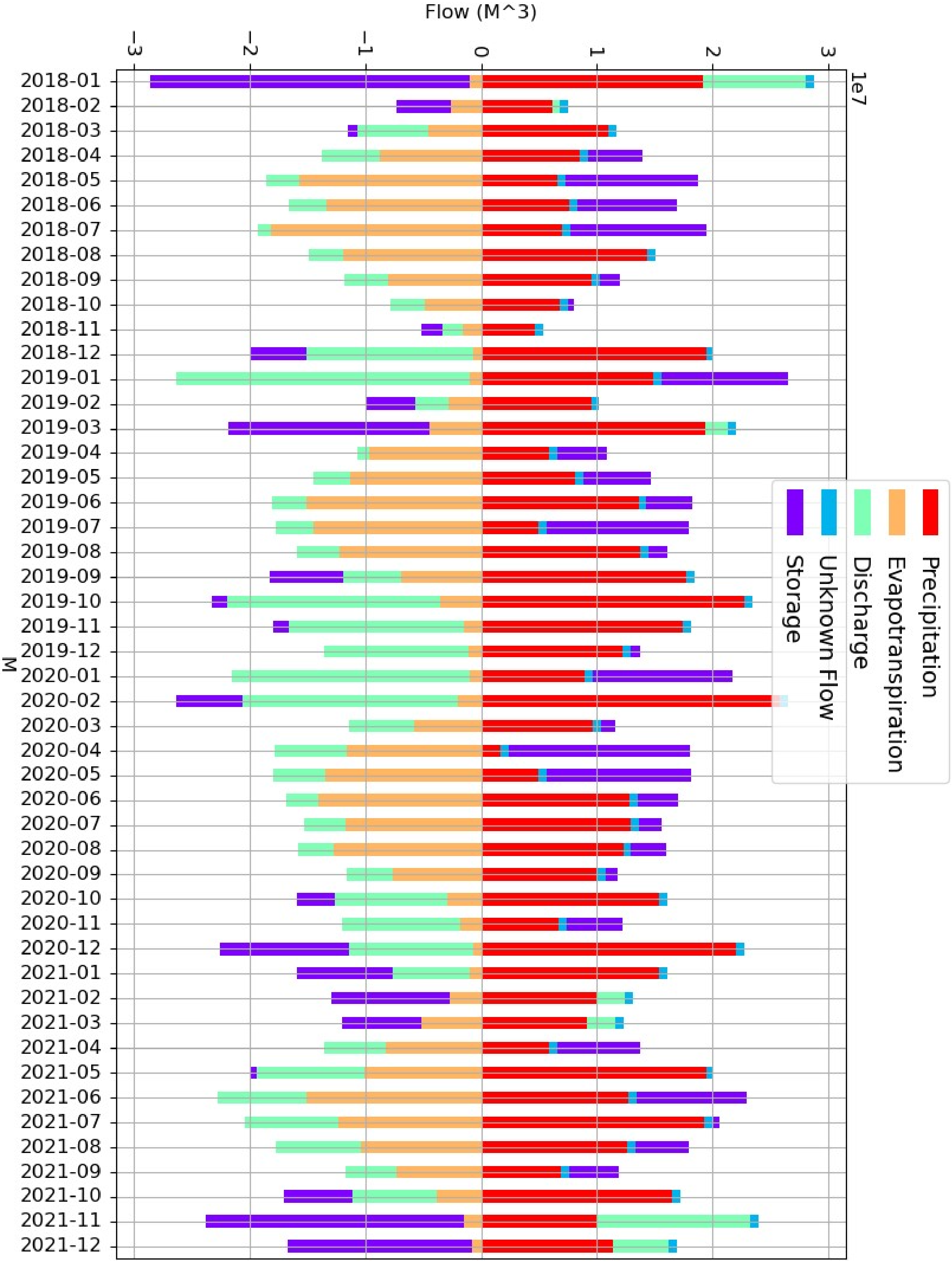


Figure 31: Net Discharge Overview graph Month

C.2 Discharge

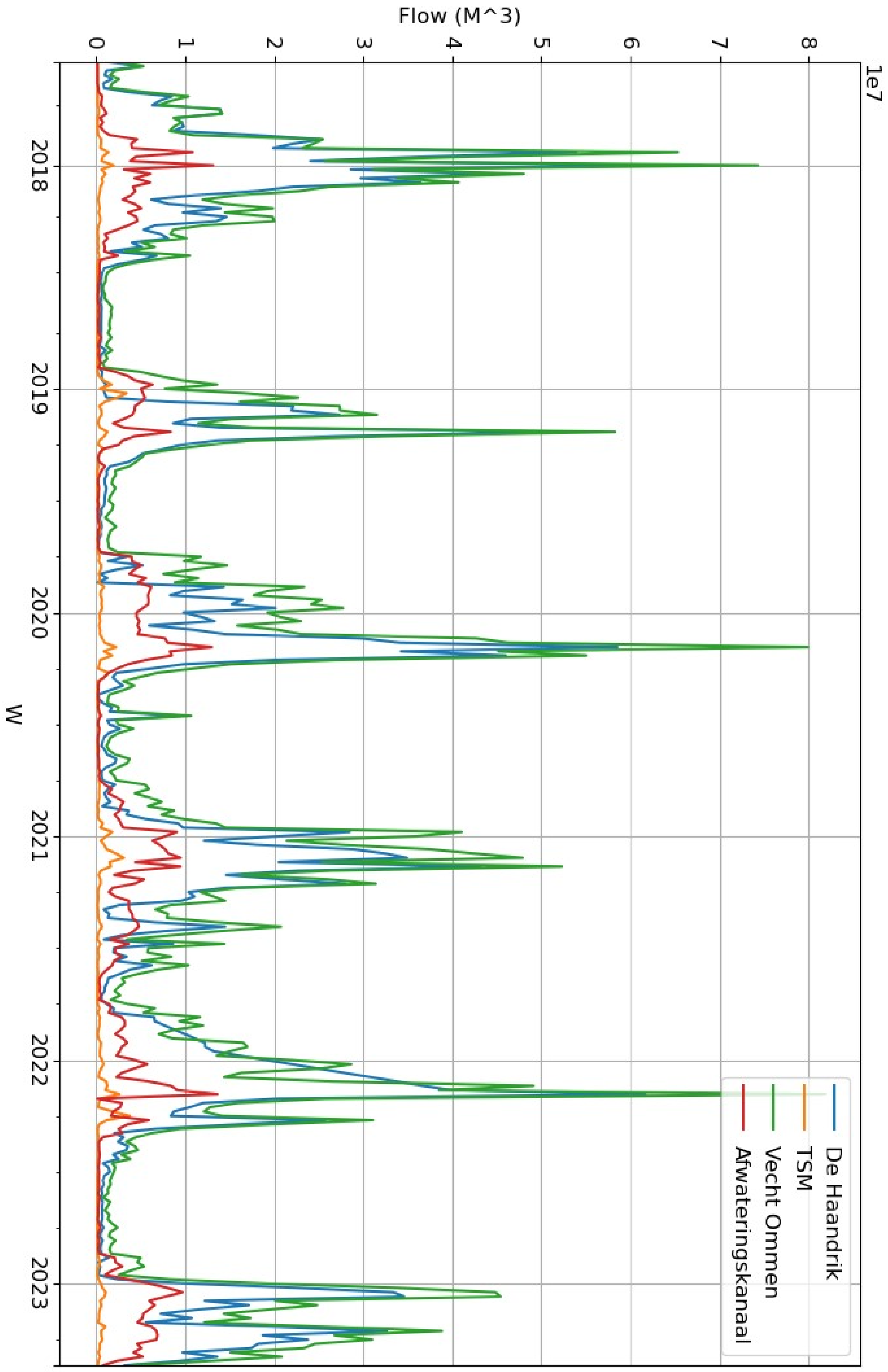


Figure 32: Overview Uncalibrated Weekly Discharge Data

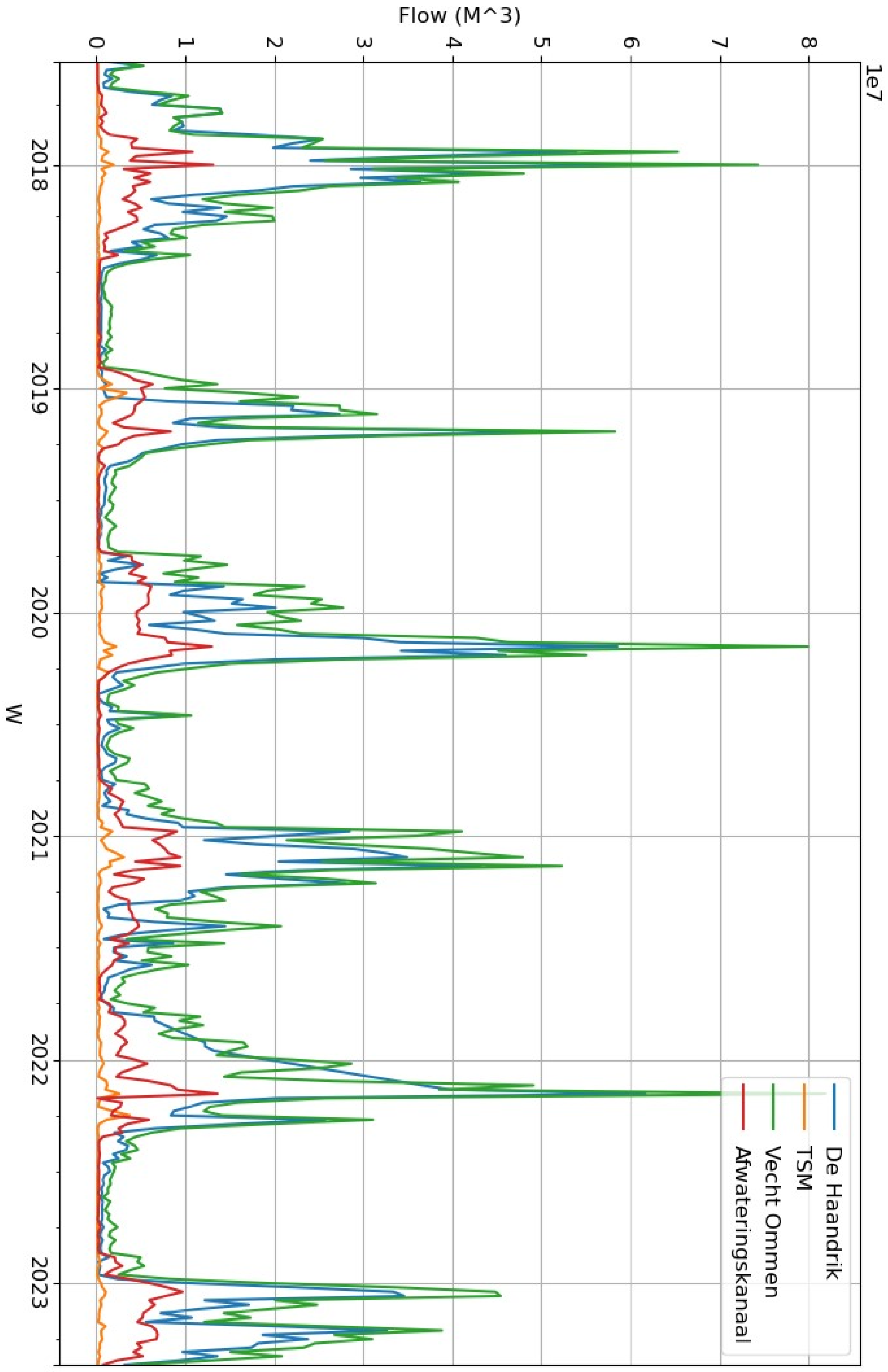


Figure 33: Overview calibrated Weekly Discharge Data

C.3 Precipitation and evapotranspiration

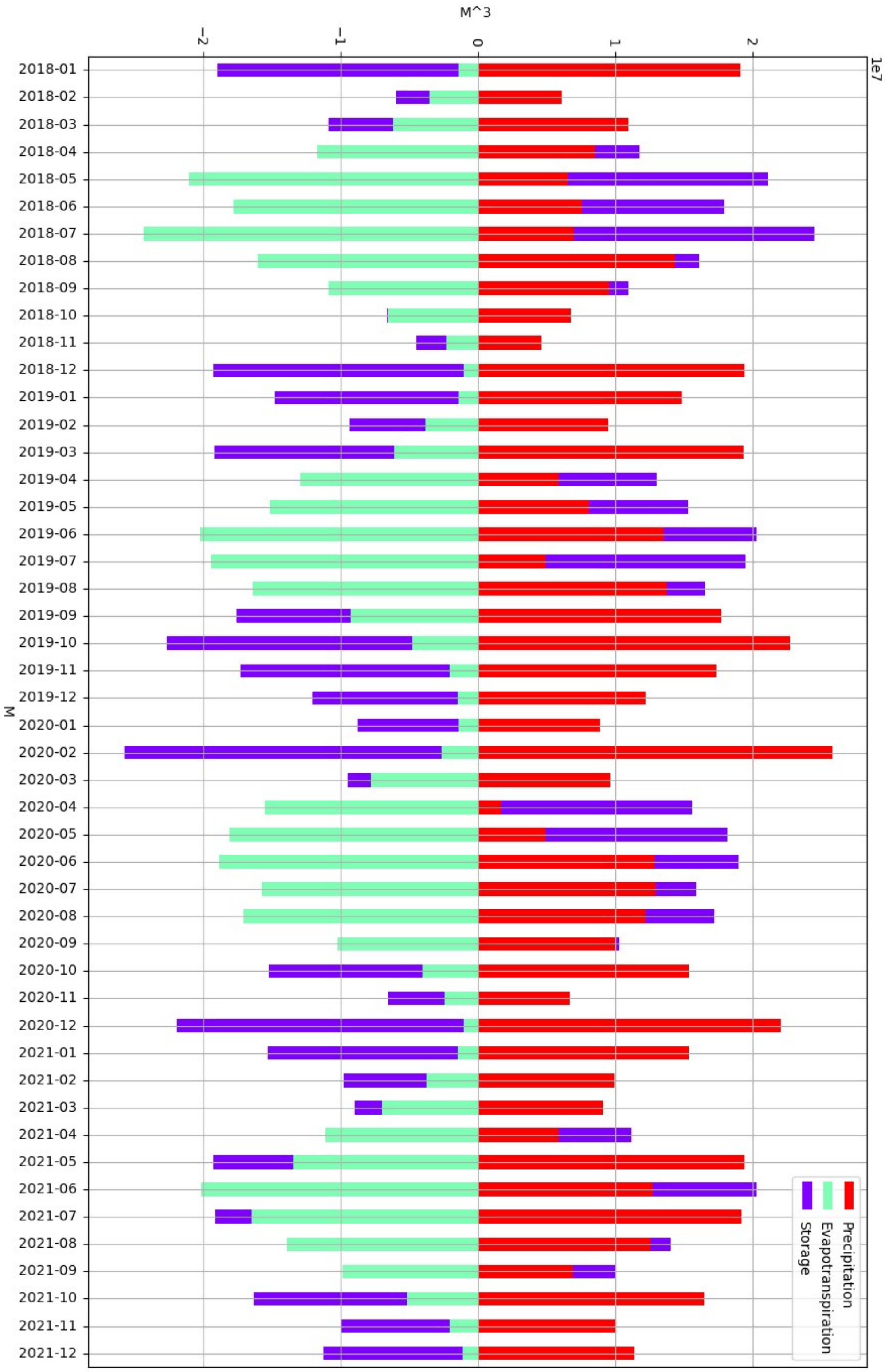


Figure 34: Overview Monthly Precipitation and Evapotranspiration

C.4 Groundwater graph

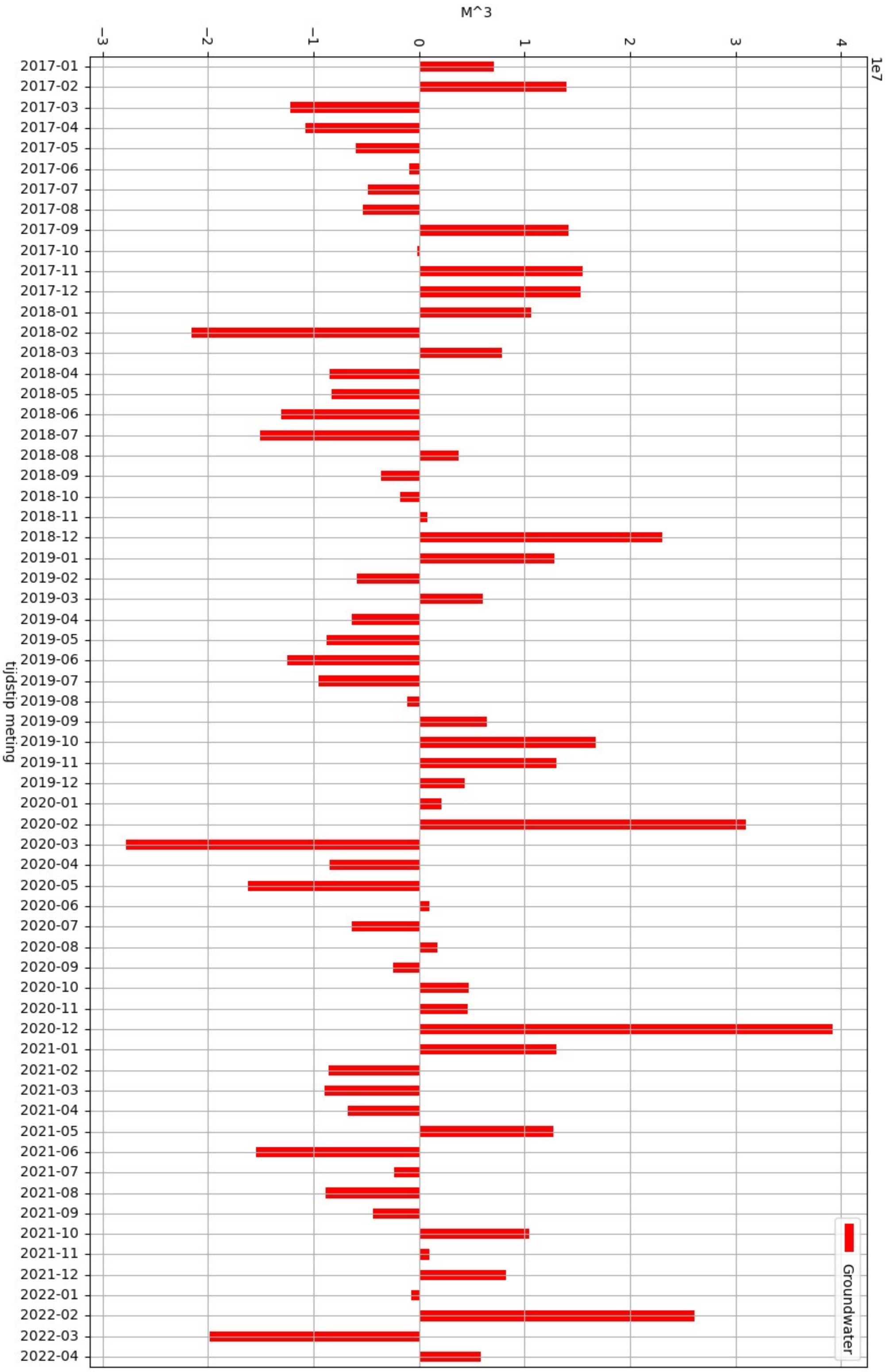


Figure 35: Overview Groundwater Flows

D Model code

The source code of the model can be found at https://wybrendejong.nl/bsc-thesis/

D.1 Import module

```python
def dataimport(path, format, indexcol, datacol, skiprows, commadecimal, delimiter,
                                          interval, proc_type):
    # Read out the CSV, define index and datacolumn
    df = pd.read_csv(path, usecols=[indexcol, datacol], skiprows=skiprows, delimiter
                                              =delimiter, skipinitialspace=True)
    # If the data uses comma's, then change comma's into points
    if commadecimal == True:
        df = df.replace(',', '.', regex=True)
    # Convert indexcolumn to datetime format
    df[indexcol] = pd.to_datetime(df[indexcol], format=format,errors='coerce', utc=
                                              True)
    # Drop NAN's
    df.dropna(subset=[indexcol], inplace=True)
    # Convert DataFrame to floats (otherwise errors occur)
    df[datacol] = pd.to_numeric(df[datacol], downcast="float")
    # Calculate respective output values based on input parameters, by using
                                              interval.

    if proc_type == "mean":
        output = df.groupby(pd.PeriodIndex(df[indexcol], freq=interval))[datacol].
                                                  mean()
        output.index.name = interval
        return output
    if proc_type == "sum":
        output = df.groupby(pd.PeriodIndex(df[indexcol], freq=interval))[datacol].
                                                  sum()
        output.index.name = interval
        return output
    if proc_type == "dm":
        df[datacol] = df[datacol].clip(lower=0) # Removes minus values
        df[datacol] = df[datacol]*3600
        output = df.groupby(pd.PeriodIndex(df[indexcol], freq=interval))[datacol].
                                                  sum()
        output.index.name = interval
        return output
    else:
        print("invalid processig type input, only mean or sum is allowed")
```

D.2 Precipitation module

```
# precipitation module, if enabled by user interface
if precipitation_button_var.get() == True:\
    # Import data
    pr_data = dataimport(pr_path,pr_format,pr_indexcol,pr_datacol,pr_skiprows,
                                                    pr_commadecimal,pr_delimiter,interval,
                                                    pr_type)
    # Select range based on start and end date
    pr_datasel = pr_data.loc[start_date:end_date]
    # Convert 10th of mm to m, multiply it by the surface area of area 1
    P_surf1 = (pr_datasel/10000)*area_1_surf
    # Convert 10th of mm to m, multiply it by the surface area of area 3
    P_surf3 = (pr_datasel/10000)*area_3_surf
    # Multiply by calibration factor
    P_sum = float(P_fac_button.get()) *(P_surf1 + P_surf3)
    # Add to output
    output.append(P_sum)
    outputnames.append('Precipitation')
    output_length=P_sum/P_sum
# If not enabled:
else:
    P_surf1 = 0
    P_surf3 = 0
    P_sum = 0
```

D.3 Evapotranspiration module

```
# Evapotranspiration module, if enabled by the user interface
if evapotranspiration_button_var.get() == True:
    ev_data = dataimport(ev_path,pr_format,pr_indexcol,ev_datacol,ev_skiprows,
                                                    pr_commadecimal,pr_delimiter,interval,
                                                    pr_type)
    # Select range based on start and end date
    ev_datasel = ev_data.loc[start_date:end_date]
    # If makkink is enabled in the user interface
    if makkink_button_var.get() == True:
        # For both area's multiply the calibration factor times the amount of
                                                        evaporation in meters and the
                                                        surface area
        E_sum_surf1 = -float(Ev_fac_button.get()) * (ev_datasel/10000) * (
                                                        area_1_surf)
        E_sum_surf3 = -float(Ev_fac_button.get()) * (ev_datasel/10000) * (
                                                        area_3_surf)
    else:
        E_sum_surf1 = -0.85*(pr_datasel/10000)*(area_1_surf)
        E_sum_surf3 = -0.85*(pr_datasel/10000)*(area_3_surf)
    # Calculate precipitation sum based on two area's
    E_sum = E_sum_surf1 + E_sum_surf3
```

```
    # Add to output
    output.append(E_sum)
    outputnames.append('Evapotranspiration')
    output_length=E_sum/E_sum
# If not enabled then:
else:
    E_sum = 0
    E_sum_surf1 = 0
    E_sum_surf3 = 0
```

D.4 Discharge module

```
# Discharge module vecht river and branches, 4 measuring points
if discharge_button_var.get() == True:
    dm_afwateringskanaal_data = dataimport(dm_afwateringskanaal_path,dm_format,
                                              dm_indexcol , dm_datacol,dm_skiprows,
                                              dm_commadecimal,dm_delimiter,interval,
                                              dm_type)
    dm_dehaandrik_data = dataimport(dm_dehaandrik_path,dm_format,dm_indexcol,
                                              dm_datacol,dm_skiprows,dm_commadecimal
                                              ,dm_delimiter,interval,dm_type)
    dm_tsm_data = dataimport(dm_tsm_path,dm_format,dm_indexcol,dm_datacol,
                                              dm_skiprows,dm_commadecimal,
                                              dm_delimiter,interval,dm_type)
    dm_vechtommen_data = dataimport(dm_vechtommen_path,dm_format,dm_indexcol,
                                              dm_datacol,dm_skiprows,dm_commadecimal
                                              ,dm_delimiter,interval,dm_type)
    #Get selection and multiply by calibration factor
    dm_afwateringskanaal = float(dm3_button.get()) * dm_afwateringskanaal_data.loc[
                                              start_date:end_date]
    dm_dehaandrik = float(dm2_button.get()) * dm_dehaandrik_data.loc[start_date:
                                              end_date]
    dm_tsm = float(dm1_button.get()) * dm_tsm_data.loc[start_date:end_date]
    dm_vechtommen = float(dm4_button.get()) * dm_vechtommen_data.loc[start_date:
                                              end_date]
    # General Q_in and Q_out of system
    Q_in = (dm_dehaandrik + dm_tsm + dm_afwateringskanaal)
    Q_out = dm_vechtommen
    Q_net =  Q_in - Q_out
    output_length = Q_net/Q_net
    # If netto discharge then plot Q_in and Q_out seperately
    if dischargenet_button_var.get() == False:
        output.append(Q_in)
        outputnames.append('Discharge in')
        statsfunc("qin", "Avarage Surf. Dis Inflow:", round(Q_in.mean(), 2), "m3")
        output.append(-Q_out)
        outputnames.append('Discharge out')
        statsfunc("qout", "Avarage Surf. Dis. Outflow:", round(Q_out.mean(), 2), "m3
                                                  ")
    elif dischargenet_button_var.get() == True:
```

```
        output.append(Q_net)
        outputnames.append('Discharge')
        statsfunc("qnet", "Avarage Netto Surf. Dis.", round(Q_out.mean(), 2), "m3")
    # If discharge analysis is enabled, calculate additional data and statistics
    if dischargeanalysis == True:
        # Relative values
        dm1 = (dm_tsm/dm_vechtommen)
        dm2 = (dm_dehaandrik/dm_vechtommen)
        dm3 = (dm_afwateringskanaal/dm_vechtommen)
        pr_rel = ((P_sum)/dm_vechtommen)
        dm_rest = 1 - (dm1+dm2+dm3)
        # Statistics
        statsfunc("dm2", "Rel. inflow Haandrik:", round((100*dm2.mean()), 2), "%")
        statsfunc("dm3", "Rel. inflow Afwateringskanaal:", round((100*dm3.mean()), 2
                                                   ), "%")
        statsfunc("dm1", "Rel. inflow TSM:", round((100*dm1.mean()), 2), "%")
        statsfunc("dm_rest", "Relative Remainder:", round((100*dm1.mean()), 2), "%")
        statsfunc("prrel", "Rel. Precipitation:", round((100*pr_rel.mean()), 2), "%"
                                                   )
# If module is not enabled
else:
    Q_in = 0
    Q_out = 0
    Q_net = 0
    print("discharge false")
```

E Additional photographs

Figure 36: Photo: Recreational use of the Vecht river

Figure 37: Photo: Vecht river

Figure 38: Photo: Kanaal Almelo-de Haandrik

Figure 39: Photo: The vecht coming from Germany at de Haandrik

Figure 40: Photo: NS Spoorbrug, close to one of the measuring points

Figure 41: Photo: Entrance sluice de Haandrik