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Track: Climate Change

Analysis of the impact on vegetation along wetlands of climate-induced changes in groundwater levels. The Flemish Kalkense Meersen case study.

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List of Abbreviations

INBO – Research Institute for Nature and Forest

GWDTV – Groundwater dependent terrestrial vegetation

FCA – Flood control area

FCA-RT – Flood control area with reduced tides

BVM – Biological valuation map

MLW – Mean low groundwater

MHW – Mean high groundwater

MSW – Mean spring groundwater

Abstract

This research focuses on the effects of climate change on water levels fluctuations and, as a result, on wetlands. The majority of climate models predict that climate change will primarily impact extreme events, leading to an increase in the frequency and intensity of both droughts and floods, and so to higher peak flows and deeper low flows. The study aims at investigating how this anticipated impact will affect the well-being of wetland ecosystems over different scenarios. Wetlands are globally recognized as ecosystems that serve vital ecological functions and hold significance as cultural and natural heritage sites. The specific wetland under examination is situated along the Flemish Sigma Plan, within the Kalkense Meersen Cluster, in Belgium. The Sigma Plan is a network of flood control areas established along the Scheldt River since 1976. This river naturally experiences tidal influence from the North Sea, allowing extraordinary natural growth along its banks but also posing a significant flood risk to adjacent areas. The Sigma Plan was initiated with the dual objective of protecting the land through water regulation and restoring the unique vegetation along the riverbanks. The Research Institute for Nature and Forest (INBO) has compiled a list of target habitats with high ecological value, found in the Sigma areas, including the Kalkense wetland, crucial for preservation and establishment under varying climatic scenarios. The work consists in an analysis of the actual summer groundwater levels of the wetland, expected to be the most impacted by climate change. These levels are estimated through hydrological conceptual models, run for three different scenarios, namely current, future without water-management and future with water-management to contrast climate change, and compared with the ideal ranges of groundwater required by each habitat as designated by the Niche model for Flanders. The latter is an important Flemish eco-hydrological tool that offers insights into the ideal abiotic requirements for groundwater-dependent ecosystems. The comparisons are visualized through spatial maps with a resolution of 10x10 meters, where each pixel is color-coded according to its actual water level condition relative to the ideal one. The results show that, under the current scenario, many habitats are in optimal conditions, while others are more at risk because closer to critical values. Conversely, a future scenario without management demonstrates that failing to take action against climate change results in a decline in aquifer storage and subsequent deterioration of conditions for many habitats. On the contrary, a future scenario with artificial hydrological management demonstrates the potential to restore current conditions. Finally, the study identifies alternative water-management actions that could yield economic and ecological advantages, compared to the current condition.

Chapter 1 - Introduction

1.1 Terminology

This thesis establishes a connection between hydrology and ecology, which is reflected in the terminology used—often a mixture of these two scientific disciplines. In this initial section, key terms are provided alongside their definitions, aiming to enhance the overall clarity and effectiveness of the text.

Ecosystem: "*An ecosystem includes all the living things (plants, animals and organisms) in a given area, interacting with each other, and with their non-living environments*" (Melissa Murray-Australian Museum, 2018).

Habitat: "*A habitat is the natural home or environment of a plant, animal, or other organism. It provides the organisms that live there with food, water, shelter, and space to survive. Habitats consist of both biotic and abiotic factors. Biotic factors are living things. Abiotic factors are non-living things*" (Australian Museum, 2018).

Regarding this study, the term "ecosystem" predominantly pertains to wetlands, which encompass the geographical regions hosting crucial vegetation that necessitates protection and the relationship between the living and non-living things. Conversely, the "target habitats" are the settings that demand preservation due to their optimal conditions for sustaining highly biologically significant plant species. Identifying and safeguarding these habitats along the Scheldt River, both presently and in the future, is of considerable importance.

1.2 Introduction and background

Over the last few decades, climate change and its associated consequences have gained ever-increasing attention in scientific studies. This phenomenon has far-reaching effects across all aspects of life on Earth. For instance, changes in global temperatures can profoundly impact the well-being of numerous ecosystems worldwide, as well as the rising of the sea levels and the desertification of green areas.

This master thesis will tackle one field of climate change impact, namely how the variations on water levels along riverbanks can have consequences on the thriving of the riparian vegetation inside specific habitats, focusing on areas heavily influenced by human activities along the Sigma Plan, that will now be described.

This research focuses on the Scheldt River in the Flemish region of Belgium, including all its tributaries. The river in his last part in the proximity of the Dutch border flows towards an important estuary, and its vicinity to the North Sea exposes it to tidal movements, creating naturally rare tidal ecosystems that support tidal and freshwater wetlands. Historically, hard engineering structures over banks of the river led to increasing storm-driving flooding in upstream regions, which became always more apparent during the last century (Vlaamse overheid, n.d.-a). This phenomenon was clearly causing harm to nearby populations and surrounding lands.

In response to this, the Sigma Plan was initiated in 1976 in Belgium. This project involved the creation of a network of flood control areas and hydrological adjustments to protect the neighbouring regions and restore the tidal nature ecosystems and wetlands. More information can be found in section 3.1.2.

Throughout the Sigma Plan project's development, extensive hydrological research has been conducted, leading to the establishment of new goals and objectives every five years. The aim of the control areas is also to restore and preserve the biodiversity of species that thrive along the Scheldt and its tributaries, which are of unique importance and are protected under the European Natura 2000 framework. Eco-hydrology in this sense plays a central role in the Sigma Plan, as it investigates the effects of hydrological processes on the function and structure of ecosystems, as well as the impacts of biotic processes on the water cycle (Moore et al., 2015). The research conducted in this study is rooted in eco-hydrological reasoning, with the goal of contributing to the preservation and restoration over climate change scenario of the Scheldt River's exceptional natural habitats and biodiversity.

The selected study area for analysis is a wetland situated within the Kalkense Meersen Cluster in the Flemish region. This site represents a profoundly valuable ecosystem that necessitates protection. Nowadays there are no flood control projects in this area of the Sigma Plan, but management actions to elevate its groundwater level (Vlaamse overheid, n.d.-d). Wetlands offer a multitude of ecosystem services to the surrounding land and local communities. However, these vital areas face significant threats resulting from human activities, including water pollution, excessive water extraction for irrigation, and other deteriorative actions. Furthermore, the impact of climate change exacerbates these challenges. Climate change has a direct influence on wetland hydrology, particularly by altering the water levels of the water bodies that convey in its area and of the Scheldt. Given that wetland ecosystems are entirely dependent on water levels, encompassing both groundwater and inundation water, any departure from their established conditions can pose serious risks. As elucidated subsequently in more detail, climate change is anticipated to impact extreme water events such as floods and droughts, intensifying their frequency and severity (Kay et al., 2021), and the challenge of this thesis is therefore to tackle how this can have effect on the valuable vegetation of Kalkense.

The Research Institute for Nature and Forest (INBO) is one of the main responsible of the Sigma Plan monitoring. The institute in accordance with the Natura 20000 guidelines, drafted a list of target vegetation of high biological value to conserve along the banks of the Scheldt. This were determined by examining the well-developed vegetation on the Sigma and excluding consequently the trunked and unstable (*KlimaatrobuustheidSigmaplan-ConcepteindrapportKULeuven*, n.d.). At the same time the Research Institute drafted a map for each Sigma area indicating how they project to distribute spatially the habitats of each target species. The presence of these habitats would guarantee an increased ecological value, creating a natural wetland area, which is in accordance with the main objectives of the Sigma Plan. For simplicity, from now on these habitats will be referred as target habitats.

For each habitat is also provided its ideal environmental conditions in terms of water levels, retrieved by the Niche Model for Flanders. This is a specialized Belgian eco-hydrological tool that utilizes data on hydrological soil and area management to offer insights into the development possibilities of water-reliant vegetation (Callebaut et al., n.d.). In general terms, the methods used in this research all consist in contrasting actual water levels obtained through hydrological models across Kalkense Meeresen with the optimal water levels for each target habitat as stipulated by the Niche Model. This comparison allows the assessment of which target habitat is thriving under ideal conditions and which instead are experiencing or will experience adversity due to climate change's impact on water levels.

In this way, this research investigates how hydrology can predict the state of the vegetation comparing current and future conditions with ideal values, and how the climate change estimated in future scenarios can shift the water levels from their ideal state.

The target habitats represent only a fraction of the total habitats nowadays present in the wetland and across all Sigma areas. To visualize all the current habitats existing in the Sigma areas a specific shapefile is available, named the Biological Valuation Map (BWK being the Flemish abbreviation). Initially, in line with the Research Institute's objectives, the plan was to incorporate the broader range of all existing habitats into the analysis, with the aim of identifying which habitats would be impacted by climate change effects and which would remain relatively unchanged. This inclusive strategy was intended to enhance the research's value and assist the institute in its investigations, since the target habitats and their spatial positions is a proposal that can be further enriched. However, it's worth noting that the forthcoming analysis, particularly in Chapter 3, retains significance when exclusively applied to the designated target habitats rather than all the current habitats. This is primarily because the Niche Model operates exclusively within the context of a specific vegetation type known as groundwater-dependent terrestrial vegetation, where terrestrial indicates that the open water vegetation is excluded from the model's analysis. Most target habitats represent the suitable environment for vegetation types that rely heavily on groundwater resources, thus are considered by the Niche model, while almost all the current habitats indicated in the Biological Valuation Map are for the time being discarded by the Niche Model. Therefore, the comparison methodology is confined solely to the target habitats. Future research should find other methodologies able to investigate the conditions and risk of every habitat thriving on the banks.

As previously mentioned, climate change is forecasted to contribute to heightened extremes in weather events. The impact in terms of fluctuations of the water levels for the Sigma areas can be translated mainly in three types: changed high water conditions in terms of overtopping frequency, changed groundwater level, changed inflow of precipitation runoff (*KlimaatrobuustheidSigmaplan-ConcepteindrapportKULeuven*, n.d.). Given that the Niche Model is designed for groundwater-dependent vegetation and considering that summer droughts are anticipated as a paramount climatic risk for wetlands (Čížková et al., 2013), special emphasis has been placed on groundwater levels and their influence on these habitats throughout the research. Concurrently, recognizing the substantial risk posed by floods, exploratory analyses have also been conducted in this direction with a relatively diminished focus.

The chosen methodology has been applied and tested within the Kakense Meersen wetland serving as the study area. There exists the possibility of replicating this methodology across all the areas designated under the Sigma Plan, which encompasses flood control areas and the depoldering zones; thus, this thesis represents a first step for a wider application. This prospect represents a potential avenue for future research expansion.

The second chapter of this thesis will present a comprehensive literature review focusing on the key aspects of the research, including climate change, wetlands, and previous methodologies utilized to evaluate the influence of climate change on wetlands' vegetation. Following this, the chapter dedicated to materials and methods will outline the study area, the materials available, the models employed, and the approach taken. Subsequently, a chapter is dedicated to the results showing all the maps retrieved according to the different methodologies and model scenarios, followed by a discussion, limits and conclusions of the research.

1.3 Aim of the research

This works aims at contributing to the eco hydrological research conducted by INBO about the actual and future state of target vegetation along the Scheldt River, more specifically along a wetland.

Among the objectives of the Sigma Plan for each area there is the restoration and conservation of the most ecologically valuable vegetation.

INBO has compiled a list of the target vegetation and spatial distribution of its habitats that is important to conserve and find along the Sigma Plan, and asked for help in assessing whether the habitats will meet ideal conditions over any climate scenario.

In this research therefore the focus is put on investigate through a hydrological model whether the ideal water level conditions for each habitat is met today, and in the future considering the predicted impacts of climate change on the water levels, more specifically on the groundwater levels which are the most critical factor for a wetland.

For each scenario of the hydrological model, a comparison with ideal ranges of low water showed the expected influence of a changing climate towards the target vegetation.

The questions posed for this research can be summarized as follows:

- Can numerical models predict vegetation development under different climatic scenarios?

- How will the conditions of the vegetation change in future if no action against climate change is taken, or better, if the management is kept the same as in the current climate?
- How will the conditions of the vegetation change in future if hydrological management actions are taken for the Kalkense wetland to contrast the predicted lowering of the groundwater?
- Can alternative water-management actions be identified, that could yield economic and ecological advantages compared to the current condition? And at the same time, are current conditions good effectively for the target habitats?

This research intends developing methodologies that link hydrology to vegetation development to investigate climate change impacts for the wetland, that could be replicated for all the other Sigma Plan areas by INBO and by all the managers taking care of the ecological aspects.

Furthermore, in this work is investigated an approach found very rarely among the scientific literature, consisting in comparing the actual water levels with ideal ones, specific for each vegetation type inside the target habitats.

1.3.1 The target habitats

In this section is reported a more insight of the target habitats listed by INBO for the entire Sigma Plan. In particular a table shows for each habitat, its official code from the biological valuation map (alphabetic), the corresponding Natura 2000 code (numeric), and the scientific name (Ecopedia, n.d.). A through foul descriptions of each habitat's features and characteristics is reported in the Appendix A.

Tale 1 Target habitats list (Ecopedia, n.d.)

Habitat code	*Habitat name*
ae, 2190	Eutrophic waters
da, 1310	Salt marshes
ds, 1130	Mudflats
ha, 2330	Bent grass vegetation
hc, 6410	Marigold grassland
hf, 6430	Meadowsweet

hp*	Species-rich permanent cultivated grassland
hpr*	Species-rich permanent cultivated grassland
hu, 6120	Mesophilic hayfield
mc, 2190	Large sedge vegetation
mr, 7140	Reedland and other Phragmition vegetations
qs, 9120	Sour oak forest
sf, 2180	Moist willow thickets on nutrient-rich soil
va, 91E0_va	Alluvial alder-ash forest
vm,91E0_vm	Alder swamp forests
vn, 91E0_vn	Nitrophilic alluvial alder forest

This table shows all the valuable habitats present in the Sigma Areas that must be preserved. Zooming on the Kalkense's wetland, the target habitats projected here are:

- **ae, hc, hf, hp*, hpr*, hu, mc, mr, va.**

Finally, the habitats analysed by the Niche Model for which the data were available for this research are:

- **hc, hu, hpr*, hf, mc, sf, vn.**

This underline a first important limitation of the research, which is the restricted number of target habitats that is possible investigate.

Chapter 2 - Literature review

This literature review aims to position the thesis topic within the existing scientific literature concerning the potential risks posed by climate change to vegetation habitats, with a special emphasis on wetland ecosystems. Wetlands are recognized for their significant ecological functions and services, including water conservation, biodiversity protection, and hydrological regulation (Fu et al., 2020). The Millennium Ecosystem Assessment Program, 2005 highlights climate regulation as their most crucial service. However, these essential ecosystems are vulnerable to human activities and the changing dynamics of our evolving climate.

This review synthesizes the body of literature focused on the central themes of this research. It begins with a general introduction on wetlands and the expected consequences of climate change on them and their habitats.

Of particular significance are the habitats listed by INBO and simultaneously studied through the Niche Model. These habitats represent the ideal environment for the growth of a specific type of vegetation known as groundwater-dependent vegetation. Consequently, an explanation of this vegetation type follows, along with the possible effects climate change might have on it.

The subsequent section delves into an exploration of climate change itself, with outlines of its potential impact on river flows, which forms the core of the hydrological investigation in this thesis.

Furthermore, this literature review explores diverse methodologies used worldwide to examine the impact of climate change on wetland ecosystem functions and dynamics. This not only situates the current research within a broader context of inquiry but also identifies its potential contribution to this evolving field of study.

Moreover, a thorough examination of current conservation and adaptation state for these ecosystems is presented. This exploration aims to compare the conservation considerations that this research will generate and, simultaneously, to explore from existing literature solutions that may align with the Kalkense Meersen area.

2.1 Wetlands ecosystem

According to (Ramsar, 1971), wetlands are defined as "*areas where water is the primary factor controlling the environment and the associated plant and animal life. They occur where the water table is at or near the surface of the land, or where the land is covered by water*".

These distinct ecosystems come into existence at the intersection of land and water and are commonly categorized as outlined by Ramsar (1971):

- Marine: Including coastal wetlands like coastal lagoons, rocky shores, and coral reefs.
- Estuarine: Encompassing areas such as deltas, tidal marshes, and mangrove swamps.
- Lacustrine: Relating to wetlands connected with lakes.
- Riverine: Encompassing inland wetlands found along rivers and streams.
- Palustrine: This category, meaning "marshy," includes wetlands such as marshes, swamps, and bogs.

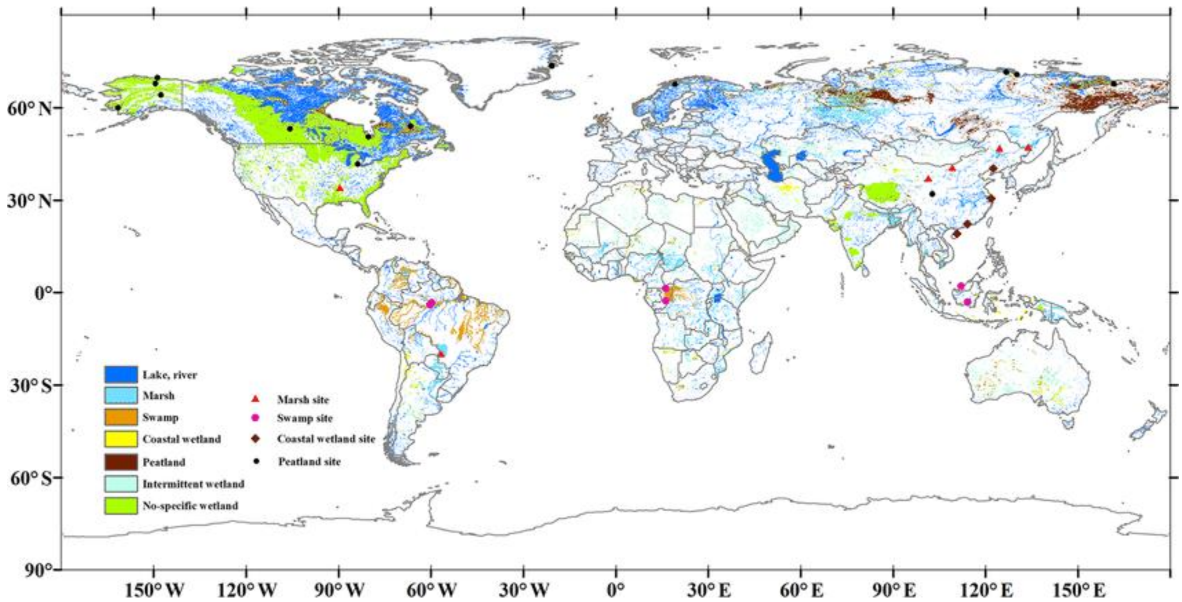

Figure 1 Global wetlands map (Li et al., 2020) as cited by (Lehner & Döll, 2004)

Each of these wetland typologies encompasses highly distinct habitats, subject to varying stressors, and therefore demanding unique adaptation and restoration approaches (Erwin, 2009).

Wetlands stand as natural reservoirs of biodiversity, providing an ideal habitat for numerous plant and animal species. This intrinsic value has raised a global imperative for their protection (Caldwell et al., n.d.). Worldwide instances showcase the ecological uniqueness of wetlands, like tropical wetlands harbouring mangroves, remarkable plants capable of thriving in tidal environments by breathing underwater and above. Moreover, these areas serve as sanctuaries for various animals and their eggs.

As stated by the Environmental Department of the European Commission (European Commission, n.d.) , when wetlands function in their natural state, they serve several critical functions: they act as natural flood buffers by absorbing water like a sponge before it flows into rivers or other streams. Additionally, they contribute to enhanced water quality, aid in reducing the concentration of greenhouse gases (GHGs) in the atmosphere, store carbon, and hold great value as both cultural and natural heritage sites (European Commission, n.d.). Among various wetland ecosystems, peatlands stand out due to their high carbon density. As a result, they play a vital role in the global carbon cycle and in addressing climate change, making climate change mitigation one of their significant services (Salimi et al., 2021). Through the process of photosynthesis, wetlands capture and store carbon by converting it into plant biomass or organic matter within the soil (Laiho, 2006). This carbon sequestration occurs effectively due to the oxygen-deprived conditions resulting from the presence of water (Laiho, 2006).

Despite their importance, wetland loss is a global concern, leading to the need of protection plans through the Natura 2000 network within the European Framework.

From a hydrological perspective, wetlands distinguish themselves by the proximity of their water surface to the ground surface, setting them apart from terrestrial and aquatic ecosystems (Epa, 2008). Typically existing in low-energy environments with gentle topography, wetlands possess a vital role in moderating water, and during wet weather, their expansible surface area accommodates changing water levels, mitigating flood flows and reducing water velocities (Epa, 2008).

(Wilen, 2013) proposes a valuable classification of wetland types based on their systems (e.g., Marine, Estuarine, Riverine, Lacustrine, etc.), subsystems (e.g., subtidal, tidal, intertidal, etc.), and bed typology. This thesis focuses on a Flemish wetland categorized as a tidal riverine wetland, being adjacent to the Scheldt River, which is influenced by the tidal rhythms of the North Sea.

According to the Flanders Environmental Agency (flanders environment agency, n.d.), despite their crucial role in combating climate change in Flanders, wetland coverage has diminished by 75% over the past 50 to 60 years. A comprehensive approach is already going on in the Flemish region, aimed at restoring wetlands to counteract climate change, safeguard against extreme water conditions (like droughts and floods), and at the same time raise public climate awareness (flanders environment agency, n.d.).

2.2 Groundwater dependent terrestrial vegetation

In this study, the analysis is primarily based on the findings derived from a customized model originally developed for the Netherlands but adapted to suit the specific conditions of the Flanders region. This model, known as the Niche model for Flanders, is employed to estimate the optimal conditions required for the successful growth of specific vegetation along riverbanks.

The specific vegetation under investigation in the Niche model exclusively relate to groundwater-dependent terrestrial vegetation (GWDTV), with no consideration given to open water vegetation. In this thesis, the analysis concentrates on habitats that are both listed by INBO and related to the vegetation modelled by the Niche model. This enables a comparison between their optimal conditions and the actual water levels predicted by the hydrological model.

It's important to explore previous research to find whether a meaningful relationship between the state of this vegetation and the dynamics of water level exists, ensuring that the approach presented research holds significance.

Groundwaters are fundamental resources for vegetation, as they provide the means for plants to endure dry periods through underground water storage. Individuals or ecosystems relying on groundwater incorporate these resources at various life cycle stages (Dresel & Terry, 2010). The term "dependence" implies that any alteration in groundwater levels beyond their usual range of fluctuation would negatively impact the natural functioning of the plant(Colvin et al., 2007). This underscores the significance of investigating the effects of climate change on water levels within the field of eco-hydrology.

(Johansen et al., 2018) conducted a study involving 35 ecosystems in Denmark hosting groundwater-dependent terrestrial ecosystems, many of which are protected under legislation and fall within the Natura 2000 Network. Over a continuous six-year period (2004-2010), water level data were collected and analysed in relation to vegetation presence. Utilizing statistical methodologies such as the Ellenberg moisture indicator, the study revealed correlations between water levels and the prevalence of specific species within ecosystems. Notably, bryophyte species richness was found to decline with increasing annual fluctuations in water level. Additionally, the study aimed to predict the potential impact of future water level changes on species distribution.

Similarly, a study by (Hudon, 1997) investigated the effects of water level fluctuations on aquatic vegetation within the St. Lawrence River in Canada. This research involved the collection of average monthly water level measurements over one year, combined with historical water level data to analyse changes over time. Vegetation zonation and assessment of plant biomass were conducted under varying conditions, accounting for different water regimes throughout a year. Results indicated that certain vegetation components remained unaffected by a one-year drop in water levels. However, submerged vegetation struggled to survive in drier zones, leading to shifts in species composition due to water level fluctuations. This example considered a one-year cycle, while the analysis of climate change involves a dataset spanning at least 30 years of water level data, thereby anticipating more pronounced effects.

2.3 Climate change

Climate change refers to the long-term alteration in temperature and weather patterns on Earth (United Nations, 2023). While it can be influenced by natural phenomena like solar activity and large volcanic eruptions, since the 19th century, human activities have become the primary driver, accelerating the rate of climatic changes like never before.

Distinguishing it from weather, which deals with short-term atmospheric conditions, climate encompasses a broader time frame during which rainfall patterns, temperatures, and humidity values are observed and analysed. Given this prolonged timescale, it becomes evident that climate variations have far-reaching effects on every habitat and ecosystem across the planet.

The impact of climate change is profound, particularly on the natural environment. Among all the other fields, it can cause significant shifts in river flows, leading to alterations in observed high and low flows (Kay et al., 2021).

Indeed, as emphasized by (Leta & Bauwens, 2018), the integration of hydrology and climate studies is crucial for gaining a comprehensive understanding of how present and future conditions can affect hydrological extremes. With this integrated approach, we can develop a more accurate assessment of the potential increase in both the frequency and severity of flooding events and drought occurrences. Such insights are vital for formulating effective strategies to mitigate and adapt to the challenges posed by these hydrological extremes.

The hydrological cycle of the Earth is in fact undergoing continuous changes and will continue to do so. On one side, due to the increasing concentration of Greenhouse Gases the atmosphere, temperatures rise and lead to an elevation in the saturation vapor pressure resulting in higher moisture content and a consequent increase of frequency and intensity of extreme rainfall events (Kundzewicz et al., 2010). This is expected to be more pronounced at middled and high latitudes of the planet (Dankers & Feyen, 2008).

On the other side, as highlighted by (Kumar, 2012), it is essential to recognize that groundwater and surface water dynamics are interconnected. Groundwater is a vital element of the hydrological cycle and, therefore, will also be influenced by climate change. Various factors will contribute to its transformation, including alterations in the interaction with surface water systems, modifications in water usage patterns, such as irrigation practices, and reduced recharge due to higher temperatures leading to increased evaporation and decreased rainfall. These combined effects are likely to result in a depletion of groundwater levels, exacerbating the issue of low water conditions (Kumar, 2012).

As underlined by the IPCC reports, climate change is projected to alter runoff and water availability, and to increase extremes of dry and wet periods (Pachauri et al., n.d.).

Zooming on the expected impacts of climate change on the estuary's ecosystems, such the important estuary of the Scheldt River, (EPA, 2023), the United States environmental protection agency, reports the followings:

1. **Rising Sea Levels:** This phenomenon inundates low-lying areas, displaces wetlands, and changes the tidal range in rivers and bays. Furthermore, it increases the vulnerability of coastal regions to storm surges during extreme weather events.
2. **Altered Rainfall Patterns:** This can result in more intense and frequent rainfall, leading to increased stormwater runoff, erosion, and sedimentation in estuaries. This

influx of nutrients, pollutants, or sediments can seriously disrupt the delicate balance of estuarine ecosystems.

3. **Droughts:** Reduced precipitation means less freshwater input into tidal rivers and bays, which, in turn, raises salinity levels in estuaries. This can have a detrimental effect on ecosystem health, as many estuarine species rely on a specific balance of freshwater and saltwater. Additionally, the intrusion of saltwater into groundwater or further upstream can pose risks to coastal drinking water infrastructure.

2.4 The effect of climate change on the Wetlands and their habitats

Climate change has the potential to exert considerable influence on wetland habitats, driven by factors such as rising temperatures, shifting rainfall patterns, the introduction of exotic species, and the occurrence of extreme climatic events, including both droughts and floods (Erwin, 2009; Salimi et al., 2021). Wetlands are recognized as resilient ecosystems due to their transitional nature between land and water, making them inherently susceptible to variations in hydrological patterns. However, the impact of climate change on water levels is reported to significantly affect their vulnerability.

A comprehensive assessment of the current state and future risks facing European wetlands, as documented by (Čížková et al., 2013), underscores that climate change will influence temperature and precipitation patterns, in turn affecting wetland habitats. According to regional climate models referenced in this study, North Europe is projected to experience the greatest warming during winter, while the South will witness this during the summer. Concurrently, augmented winter precipitation in North Europe will be counterbalanced by higher temperatures, which will decrease the snow season and snow depth while promoting evapotranspiration. This scenario suggests that summer droughts will pose the most significant climatic stressors for inland wetlands, including those along rivers (Čížková et al., 2013). (Erwin, 2009) also reports similar predictions, anticipating a heat increase in the tropics, which could lead to enhanced water vapor movement towards higher latitudes. This could result in reduced precipitation at lower latitudes and increased at higher latitudes.

The Australian Government concurs with a high likelihood of increased temperatures, precipitation changes, droughts, and floods impacting inland freshwater wetlands, and further warns of serious threats to coral reefs, mangroves, swamps, and high-altitude wetlands (Government Department of the Environment, n.d.).

The increased frequency of floods poses a significant threat to wetland ecosystems, potentially leading to waterlogging (Staes et al., 2011). This, in turn, can result in oxygen deficiency and difficulties in root respiration, particularly affecting terrestrial vegetation within wetlands. Unlike the abundant oxygen content in air, water contains significantly less oxygen, which presents a substantial risk to the respiration processes of these wetland plants. It's important to note that the impact of flooding on oxygen availability is influenced by several factors, including the initial oxygen content, the turbulence of the floodwater, the duration of the flooding event, and the water temperature (Staes et al., 2011).

In terms of wetland ecosystems, climatic degradation is expected to alter their capacity to provide the aforementioned ecosystem services. For instance, their role as water purifiers could be compromised, potentially leading to nutrient release during decomposition, causing eutrophication and acidification (Corman et al., 2018). Additionally, accelerated rates of denitrification and nitrification, coupled with a shift from carbon sink to carbon source, are linked to wetland deterioration (Laiho, 2006; Salimi et al., 2021).

Climate change will most probably lead to increase loss and deterioration not only for its action, but most of all due to the synergistic effect of non-climatic and climatic drivers, that together represents the global change (Lucas & Lloréns, n.d.). In fact is important to underline that wetlands ecosystem are already put under pressure by activities such as land use change, non-regulated fishery, water pollutions, by invasive species and many other factors. These add up to the climatic stresses, increasing the deterioration rate along with the risk of endemic species extinction and making more complex the plans aimed at restoring the ecosystems (Moomaw et al., 2018).

The ramifications of heightened hydrological variability due to climate change will reverberate across the vegetation habitats thriving within wetlands. With a specific focus on groundwater-dependent habitats, which are central to this study, the increased frequency and intensity of droughts will inevitably diminish available groundwater resources, thus impacting ecological and biological functions. Similarly, the changing trend of flooding events will necessitate a close examination of the effects on vegetation, particularly in relation to more frequent and intense water level fluctuations. A conceptual exploration by (Chiloane et al., 2022) regarding climate impact on groundwater-dependent vegetation underscores that effects depend on aquifer typology. Smaller, shallow unconfined aquifers show heightened sensitivity, while larger confined ones exhibit delayed responses. Furthermore, riparian vegetation's heightened potential for groundwater dependence renders it more susceptible to climate change impacts (Barron et al., 2014).

Similarly, also (Staes et al., 2009) reports that when talking about wetlands restoration a generalisation can't be made, due to a high variability of local conditions, and topography of the catchment. Indeed, the study in question primarily focused on the wetland's location within the catchment and the hydrological characteristics of each site.

It is imperative to underline that wetlands encompass a diverse array of ecosystems, ranging from floodplains to forests, demanding the recognition of distinct stressors and tailored management strategies for each typology (Erwin, 2009).

2.5 Methodologies approach to assess the impact of climate change on wetlands

In this section, the literature presents methodologies employed to evaluate the potential influence of climate change on wetland dynamics and their vegetation. The intention here is to comprehend how this research aligns with existing approaches in the eco-hydrology domain by integrating the proposed methodology. As will be later discussed, the methods employed in this thesis for assessing water level fluctuations and their consequences on wetland target habitats involve a comparison between actual current and future (under climate change impact) conditions estimated through hydrological models and the optimal conditions given by the Niche model for each habitat within the Flemish region.

Numerous studies have been undertaken on the Prairie Potholes wetlands in North America. For instance,(van der Valk & Mushet, 2016) utilized harmonic hydrological models to investigate the response of vegetation zones to water level fluctuations driven by climate change scenarios, including wetter and drier conditions. (Johnson & Poiani, 2016) similarly conducted research in this region over a 25-year span, combining numerical modelling with long-term surface and groundwater data to ascertain the ecological threshold causing shifts from favourable to unfavourable conditions for vegetation.

Further work on Prairie wetlands has been conducted by (Poiani et al., 1996), who employed a mathematical model encompassing hydrology and vegetation dynamics over a 32-year period. According to their report: "*One component of the model was used to calculate changes in water storage based on precipitation, evapotranspiration, snowpack, surface runoff, and subsurface inflow, while spatially explicit component calculated changes in distribution of vegetative cover and open water, depending on water depth, seasonality and existing type of vegetation*" (Poiani et al., 1996) .Withey & van Kooten, 2011 utilized linear regression analysis, incorporating temperature, precipitation, and standardized precipitation index to assess the impact of climate change in the same region.

(Rogers et al., 2014) focused on coastal wetlands and their response to sea level rise, temperature increase, and elevated carbon dioxide levels. Over a 12-year span, they examined the behaviour of mangroves and salt marshes in relation to changing climatic dynamics, comparing variables like surface elevation change, vegetation distribution, water levels, and rainfall.

In the context of riverine wetlands, (Mirosław-Świątek et al., 2020) conducted research along the River Biebrza in Poland. They analysed the impact of climate change on flood hydrological characteristics using 30 years of historical data and forecasted these changes using the SWAT model. This was complemented by a qualitative assessment of anticipated vegetation alterations by comparing projected hydrological characteristics to typical literature values.

Moreover, (Fu et al., 2020) assessed the ecological risk of wetlands by simulating plant productivity and diversity alterations in the Sanjiang Plain of China under diverse climate scenarios, employing the CMIP5 global climate model.

In a study conducted by (Staes et al., 2009)innovative methods for habitat restoration within wetlands were investigated, along with the resulting hydrological impacts of each approach. This research aimed to determine whether the topography and location of wetlands within the catchment influenced these impacts. The study area was situated in the Grote Nete catchment along the Sigma Plan region. The researchers employed a statistical model, focusing primarily on the rewetting of river valleys as the main restoration technique. They considered three distinct scenarios: restoring infiltration areas, restoring upstream headwater wetlands, and restoring downstream valley bottom wetlands. By incorporating land use data as an input into the hydrological model, the study revealed several key findings. Across all three scenarios, there was a noticeable decrease in the overland component of streamflow, accompanied by an increase in the saturated zone flow component. These changes promoted groundwater recharge. Importantly, the study found that these alterations in wetland restoration did not lead to an increase in peak flows (Staes et al., 2009).

Apart from statistical modelling approach, (Silvestri & Marani, 2013) employed a mechanistic method to gain a more detailed understanding of wetland conditions. Their research specifically focused on salt-marsh vegetation development and utilized remote sensing techniques. Through satellite imagery analysis, they examined vegetation distribution, with the Venice Lagoon as their study area, highlighting spatial patterns. The study emphasized the significance of vegetation density as a critical ecological parameter for characterizing areas favourable to plant development. The authors stressed the importance of establishing a connection between physical processes and plant physiology. While remote sensing is a valuable tool for providing data on vegetation type, abundance, and distribution, it must complement mathematical models that investigate the effects of ecological and morphological processes. Furthermore, the authors pointed out that existing mathematical models need to be enhanced with additional observation data to transition into predictive models. Presently, many of these models are capable of generating physically based conceptual representations but fall short in predicting the system's evolution (Silvestri & Marani, 2013).

2.6 Adaptation strategies for preserving wetlands biodiversity

This section focuses on the concepts of conservation and adaptation within the context of wetlands and their response to climate change. It's essential to distinguish between these terms. Conservation of natural sites aims at restoring damaged ecosystems and maintaining conditions suitable for their growth, while climate adaptation involves devising strategies for coping with current and future climatic changes and their potential effects on the environment (European Commission, n.d.).

(Kingsford, 2011) emphasizes that the effectiveness of conservation efforts greatly relies on upholding existing legislation. On an international scale, the Ramsar Convention, established in 1971, serves as a significant framework for preserving and sustainably utilizing wetlands and their resources globally (Ramsar, 2023). This global network is closely tied to its European counterpart, collaborating to protect crucial European sites through the Natura 2000 network. Natura 2000 stands as a pivotal tool in the European Union's strategy for safeguarding biodiversity. It forms a European ecological network of safeguarded areas established under the "Habitat" Directive 92/43/EEC, aimed at ensuring the ongoing preservation of natural habitats and rare or endangered flora and fauna species at a community level (natura che vale, n.d.).

Shifting our focus to the Flemish context, the Sigma Plan plays a central role in achieving conservation goals by restoring lost wetlands through hydrological management techniques. This notably includes flood control areas with regulated tidal influences, depoldering and existing wetlands management.

The Ramsar Convention employs a distinct framework, summarized as follows (Finlayson et al., 2017):

• Avoiding climate change impacts: Maintaining existing objectives and targets, particularly for short-term, highly valuable sites.

• Accommodating or mitigating climate change: Opting for interventions that cover a broader array of wetland types and diverse ecosystem services, with a focus on areas needing conservation.

• Accepting and compensating for climate change: Acknowledging that climate change can't be entirely averted, and promoting conservation objectives that demand minimal management intervention.

The second approach outlined by Ramsar aligns well with the eco-hydrological projects of INBO and the scope of this research, as it centres around conserving valuable target vegetation that is hoped to thrive along the river in the future.

As noted by (Kingsford, 2011), the approach to ecosystem conservation should adapt to the specific threats within the catchment. Identifying critical key freshwater habitats and prioritizing the management of potential threats and environmental flows becomes vital due to the anticipated impacts of climate change. The study by (Guareschi et al., 2020) delved into the patterns of habitats of conservation concern and their alignment with patterns of threatened species, suggesting that integrating both habitat and species perspectives can provide effective insights for wetland conservation and assessment. To ensure the preservation of dominant plant populations, it becomes necessary to safeguard areas that are susceptible to environmental extremes. Simultaneously, efforts should focus on restoring vital habitat structures and enhancing habitat abundance (Erwin, 2009 and their citations). Climate change might result in species being unable to locate suitable environmental conditions (i.e., their habitat), or their tolerance limits being exceeded (Finlayson et al., 2017).

This underscores the significance of localized investigation and highlights how distinct biotic and abiotic optimal conditions can differ widely among various habitats, necessitating tailored study.

(Chambers et al., n.d.) introduced a risk assessment framework designed for adapting groundwater-dependent ecosystems grappling with declining water levels due to climate change. This project identified a substantial gap in the climate adaptation domain, wherein translating into practical management tools remains challenging. In contrast, (Sarkar et al., 2016) documented various adaptation techniques that can be formulated and implemented based on expected climate change impacts on wetlands. For scenarios involving heightened drought frequency and intensity, one potential solution involves replenishing freshwater aquifers during periods of abundant water availability.

Chapter 3 – Methods and Materials

3.1. Study Area

3.1.1 The Scheldt River

The Scheldt River is a water body 245 Km long, that originates in the north part of France, crossing Belgium until it encounters the North Sea, forming an estuary in correspondence to Antwerp (Britannica The Editors of Encyclopaedia, 2023).

In its last part, when crossing the Flemish region towards the border with the Netherlands, the river is extremely influenced by the tidal movement of the North Sea, and this leads to the extraordinary vegetation typical of estuaries, with brackish water, such as salt marshes, which are spread all over the Sigma region. Despite the salt marshes habitat is listed among the target ones by INBO, it is not included in the analysis of the Niche Model and therefore not in this work.

3.1.2 The Sigma Plan

As previously introduced the Sigma Plan consists in a network of flood control areas with the dual objectives of safeguarding of the surrounding land from floods and restore the extraordinary vegetation thriving along the riverbanks.

According to the official website of the Sigma Plan, "*a flood control area is a piece of land adjacent to the river that is surrounded by a ring levee and serves as a water buffer zone in extreme weather conditions*" (Vlaamse overheid, n.d.-b). In practice, the existing previous ring is lowered and reinforced, while an outer and higher ring is built; in this way in case of extreme high water, like storms, the water overcome the inner ring, the land is flooded with water enhancing the growth of freshwater vegetation, but the neighbourhood is still protected by the second ring (Vlaamse overheid, n.d.-b). The flood control area serves mainly for the safety of the surrounding land, while other key methods are used for the restoration of tidal ecosystems, namely Flood Control Areas with reduced tides (FCA-RT) and Depoldering. FCA-RT involves constructing an inlet and discharge sluice in the original inner dike, allowing tidal water to enter the floodplain with a daily frequency from the inlet, restoring the tidal nature, while the neighbourhood land is safeguarded by another higher and outer dike or ring levee (Vlaamse overheid, n.d.-c). Depoldering, on the other hand, entails creating breaches in the original dike, enabling water to flow in and out the floodplain with its natural tidal movement, while the area remains protected by an outer high dike, leading to the development of tidal nature (Vlaamse overheid, n.d.-c).

For each Sigma Area there are specific projects aimed at valorising the land, the local economy, the tourism, and many other aspects. Below is reported a picture showing the entire Sigma Plan region with all the areas within the project, with a highlight on the very specific study area of this work, the Kalkense Meersen wetland.

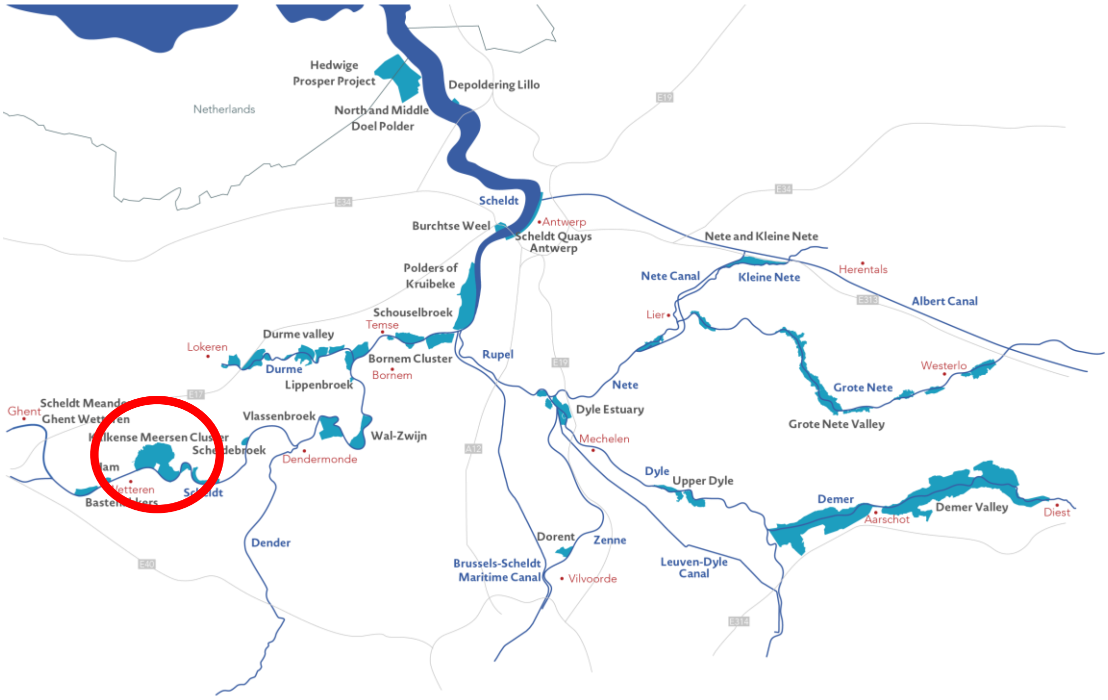

Figure 2 Position of Kalkense Meersen inside the Sigma Plan

3.1.3 The wetland

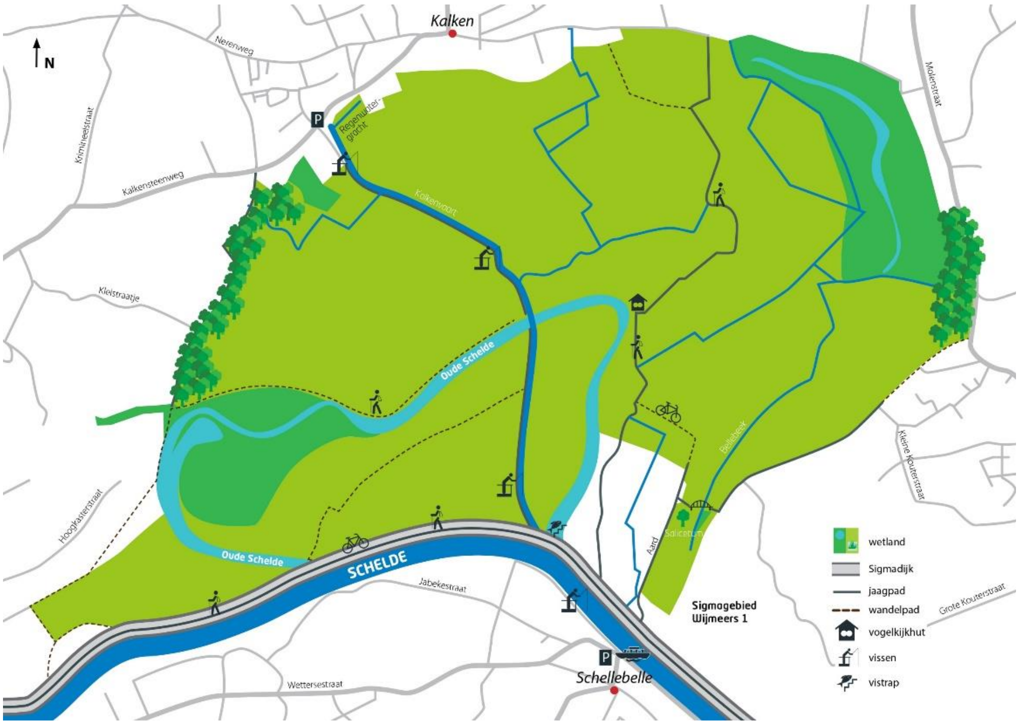

Figure 3 Kalkense Meersen (Vlaamse overheid, n.d.-d)

As mentioned in the before, the Sigma Plan is a network of natural flood control areas designed to manage excess river water in a controlled manner. These areas span the entire length of the Scheldt River, encompassing valleys, wetlands, and estuaries.

For the purposes of this thesis, the analysis has been conducted within a specific region of the Sigma Plan, namely, the wetland located within the Kalkense Meersen Cluster (*Figure 3*). The methodologies, analyses, and results discussed in this thesis are based on this area, serving as a pilot test. The intention is that these same algorithms and approaches could potentially be applied to all the Sigma Plan areas along the river in the future.

Kalkense Meersen is a designated nature reserve spanning 606 hectares across the territories of Laarne, Wetteren, Wichelen, and Berlare (Vlaamse overheid, n.d.-b). This area falls under the classification of a wetland and plays a crucial role as a natural sponge, capable of retaining excess water flowing downstream towards the Scheldt River (Vlaamse overheid, n.d.-b).

The objectives of the Sigma Plan are multi-faceted, aiming to ensure the safety of local communities against extreme events, restore the region's valuable natural ecosystems, provide recreational opportunities, and stimulate local economies (Vlaamse overheid, n.d.-

a). Kalkense Meersen, in particular, is a region with a significant local population, offering stunning landscapes that can be explored by visitors through pedestrian crossings and beautiful parks.

3.1.4 Water management in Kalkense Meersen

For the Kalkense wetland area, there are no planned flood control operations, such as depoldering or controlled tidal systems. Instead, the primary focus here is on groundwater management. It has been recognized that, both historically and in future projections, summer droughts pose a significant risk to the vegetation within and along the riverbanks of the wetland. Extended periods of drought can result in depleted groundwater reserves, endangering the survival of vegetation that relies on this water source during dry spells.

As previously mentioned, the wetland serves a critical role in retaining excess water from upstream regions, functioning like a natural sponge that temporarily stores this water before allowing it to flow into the Scheldt River. The exchange of water between the wetland and the river is regulated by a specific type of pipe known as a Culvert pipe. This mechanism helps maintaining the delicate balance of water levels in the wetland and its surroundings, contributing to the overall health and functionality of this unique ecosystem. Below is shown an example of pipe:

Figure 4 Example of Culvert rectangular pipe (Department of transportation, 2021)

The pipe adopted for Kalkense Meersen has dimensions of:

- 3 m width
- 2. 5 m height
- 2.55 m elevation from ground level

To replenish the groundwater storage, a strategic method involves modifying the outlet of the culvert pipe by covering it up to a specific level with wooden or metallic structures. In other words, the managers of the area can install a higher water level above which a pump will be activate for the water passage. By doing so, any water flowing from the wetland towards the river must surpass this designated level to enter the Scheldt. If this level isn't reached, the water will be retained within the wetland area for an extended period, gradually seeping into the soil and replenishing the groundwater reserves.

The adjustment of this pipe level can be tailored to different factors, including seasonal variations, specific weather events, or anticipated climatic conditions. It is typically after the wet winter season that the level is raised, to retain the rainfall waters. It is then decreased before the starting of the new wet season.

3.2 Materials

3.2.1 The spatial analysis

The research is based on a spatial analysis through a GIS software and on the interpretation of hydrological data. The software allows the visualization and management of the shapefiles through their attribute table, in which each row represents a certain geometrical element, for example a polygon or a pixel. In this way, is possible to visualize the map as dataset, and further investigate it with the aid of other programming languages or software such as Python and Excel. Indeed, both were used to carried out the methodologies that will be later shown.

The main available spatial data include:

- a shapefile of all the Sigma Plan areas.

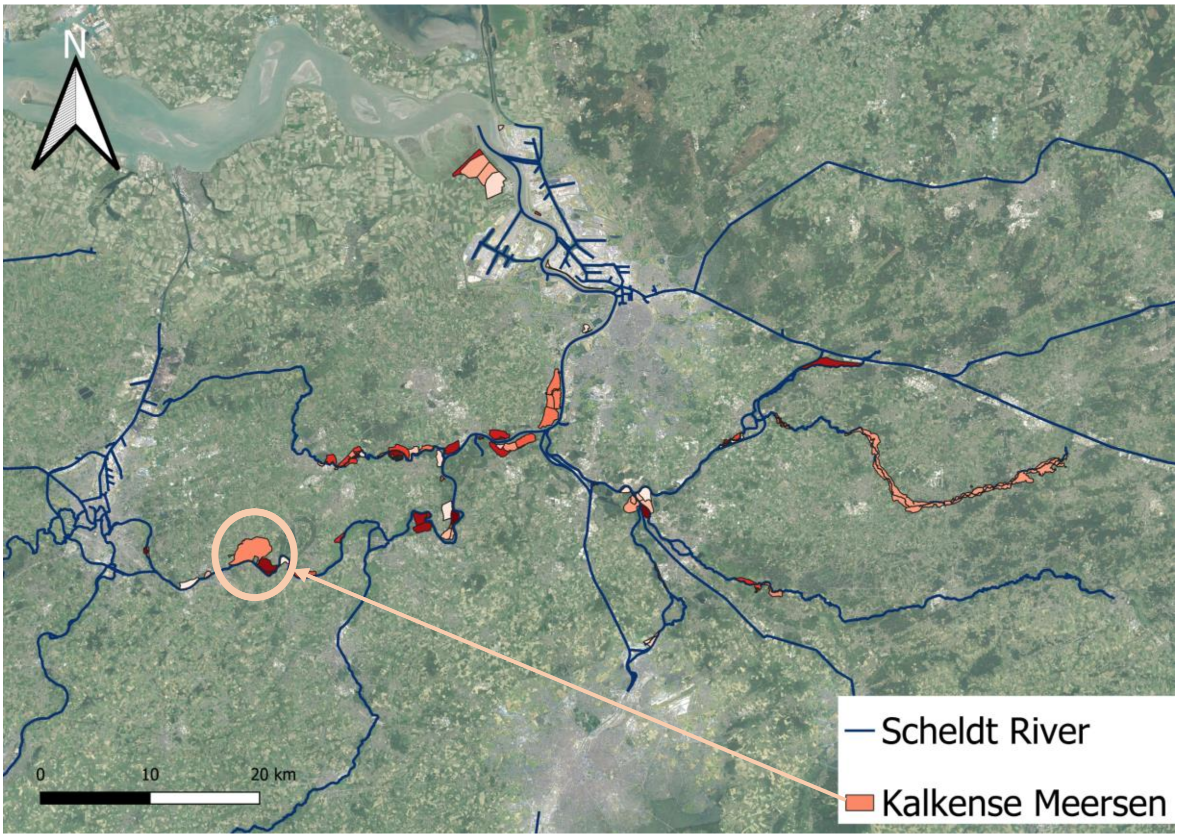

Figure 5 All sigma plan areas inside the Flemish region

- a shapefile of the Flemish soils type,

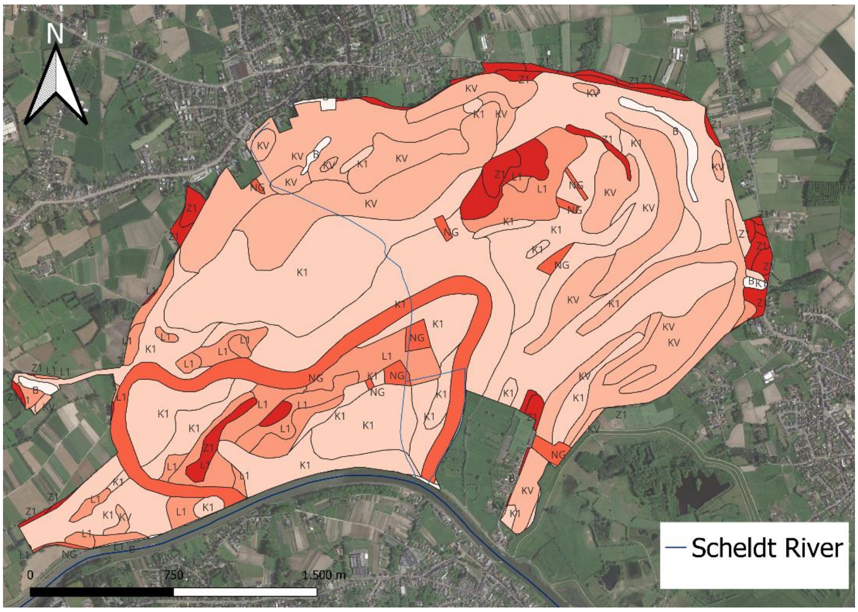

Figure 6 Flemish Soil Map zoomed on Kalkense Meersen

- a shapefile with all the current habitats present in the area,

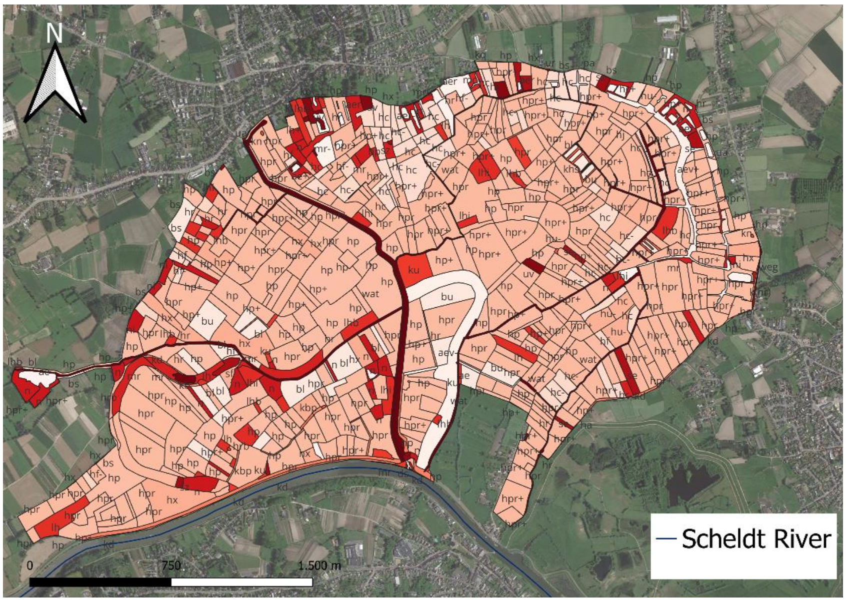

Figure 7 All current habitats in Kalkense Meersen

This layer is extracted from the Flemish Biological Valuation Map. According to (De Saeger et.al, 2020) the Biological Valuation Map (BVM) is "*a major database for land and vegetation cover of the Flemish Region in Belgium*". The map is a result of field survey computed over the years, and with multiple versions it keeps trace of the habitats and vegetation distribution of the region. Some units of the map give information of the land use type, but most of them contains a code expressed in letters which can be translated into a habitat type (De Saeger et.al 2020, 2020).

There is a link between the habitat's codes present in the map the and the European frameworks habitats. For most of the unit of biological map in fact there is a direct translation into a Natura 2000 habitat.

The map showed in the above image is zoomed on Kalkense Meersen Wetland, and is referred to the most recent biological Map, released in the year 2020. Other maps are available, such as the for the years 1997, 2014, 2016 and 2018.

The same analysis and methodologies were applied to all these maps, to the 2020 map and to the one showing only the target habitats. However, as underlined in the introduction and remarked later, at the end the results showed significance only for the target habitats map, due to an higher match between its habitats and those analysed by the Niche model.

- a shapefile with the position of target habitats that must be preserved.

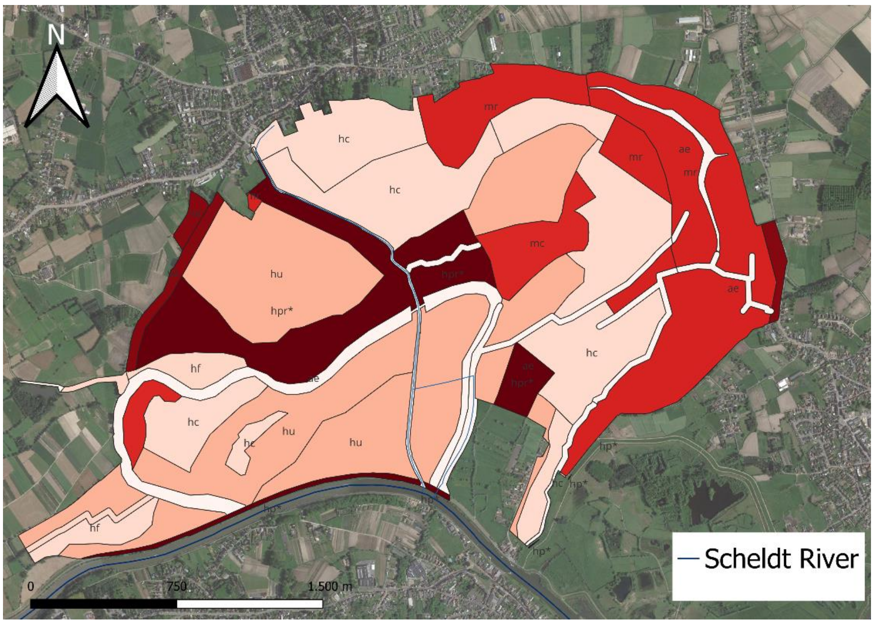

Figure 8 Target habitats map

The map showing all the current habitats and the one showing only the target habitats listed by INBO were intersected with the same Flemish soil layer used by the Niche Model, and then rasterized with a resolution of 10 x 10 m. In this way, every pixel represents an area of 10x10 m in which a certain habitat is found in a certain soil:

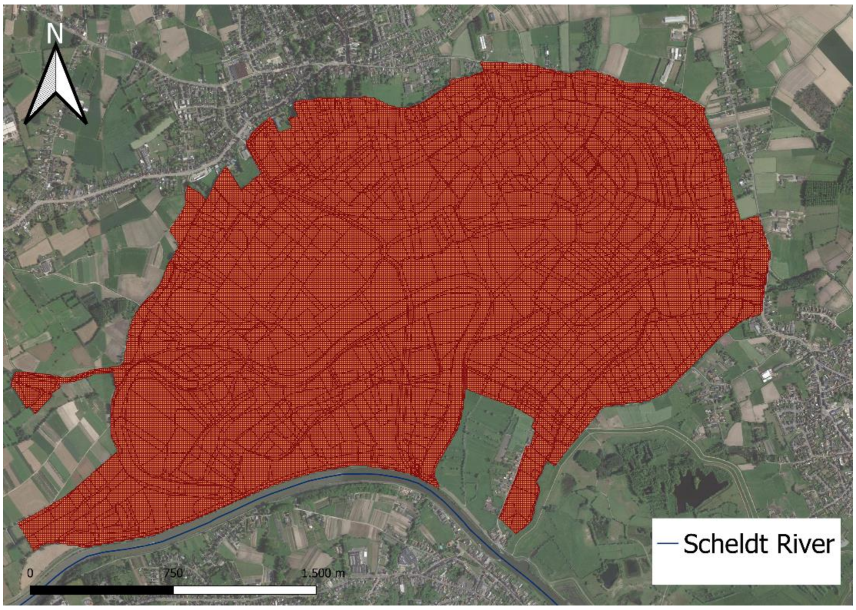

Figure 9 Soil map and all current habitats rasterized with 10x10m resolution

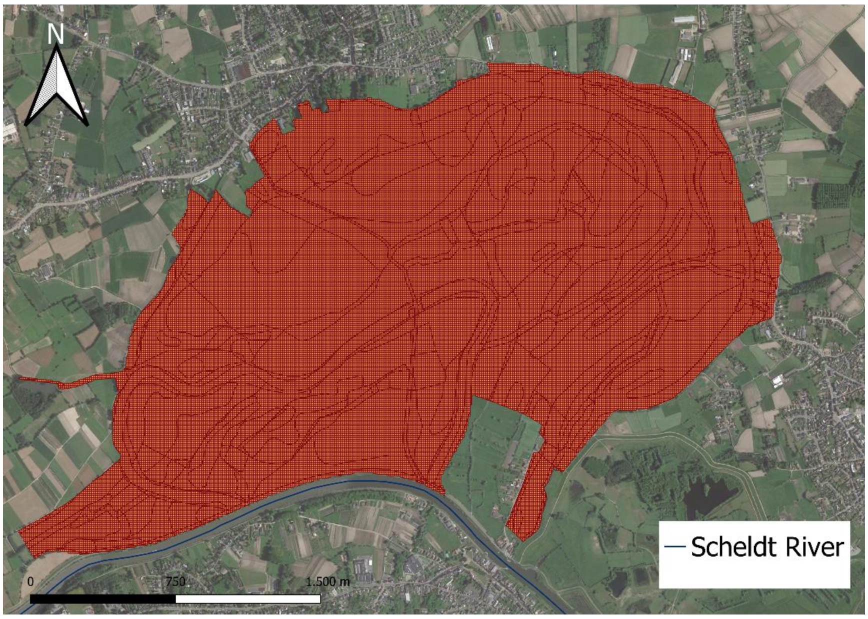

Figure 10 Soil map and target habitats rasterized with 10 x 10 m resolution

3.2.2. The Niche Model

All the information reported in this section are entirely referred to the official Niche Model for Flander report (Callebaut et al., n.d.).

Niche stands for "Nature Impact assessment of Changes in Hydro-Ecological systems", is a hydrological model that originated in the Netherland and that then was adapted for the Belgian Flemish region. The model computes potential impacts on various vegetation types resulting from alterations in water management and land use. It takes into account several key factors, including soil type, groundwater levels, soil pH, and soil nutrient content. Essentially, the model uses hydrological, soil, and land management data to offer insights into the prospects for the growth and development of water-dependent vegetation in a given area.

In order to assess the impacts on vegetation of water management and land use, site conditions are calculated based on the factors reported above, and then compared with the plants' ideal ranges of the same factors. The model in facts makes use of these important ideal ranges that have been obtained through field observations, along with expert knowledge and literature. The principle of the model states that vegetation habitats and communities "*will only remain the same if all site requirements (soil, groundwater etc..) are met*".

The soil type, as said above, is a fundamental factor that can influence the effects on the vegetation wellness. For this reason, the association habitat-soil type is also taken into consideration for this research.

The Niche model distinguishes a limited number of ecologically relevant soil units that are associated with the ideal ranges. The following soil codes are the same as those reported in the Flemish soil map:

Table 2 Niche Model's soil types

Soil code	*Soil type*
HV	High moor
K	Fluvial clay soils
KV	Clay on peat
K1, K2	Sandy soils with clay close to the ground level
L	Loam soils
MK	Marine clays soils
P	Petgat
V	Peat soils
V2	Peat with sand cover
W	Open water
Z1	Humus – poor sandy soils
Z2	Humus – sandy soils
ZV	Moist soils and sandy peat soils

Another important factor controlling the occurrence and ideal thriving of vegetation is the groundwater level, along with its fluctuations. This factor for the Niche model translates in different parameters calculated starting from water levels:

Table 3 Niche Model's groundwater parameters

Parameter	*Description*
MHW (mean high groundwater)	The average of the three highest groundwater levels in the winter period (1 October – 1 April) over the last 5 years
MLW (mean low groundwater)	The average of the three lowest groundwater levels in the summer period (1 April – 1 October) over the last 5 years
MSW (mean spring groundwater)	The average groundwater level at the beginning of growing season (1 April) over the last 5 years

The parameters MHW and MLW are of particular importance; every vegetation type grows, sustain, and thrive under optimal parameters values, and would suffer due to their shift.

In this way, the Niche model generates a habitat description in terms of ecological soil unit and optimal groundwater level through the parameters.

To sum up, the research reported in this thesis uses the ideal ranges estimated by the Niche model for a comparison with actual water levels, to investigate the habitats' wellness and distribution according to current and climate change conditions.

As said in the previous chapters, the model is limited to the analysis of groundwater-dependent vegetation, with no considerations for open water vegetation.

The Model's target areas are analysed in a uniform and transparent way, and possible scenario can be investigated. At the same time, as underlined by the authors, it presents some limits in estimating the vegetation development:

- is assumed that colonization of an area by a vegetation type doesn't encounter any natural obstacle
- the germination conditions are not taken into account
- the results are reliable only for what concerns stable communities, not trunked or disturbed
- only abiotic factors are taken into account, excluding the biotic sphere. This doesn't allow to make evolution predictions.

In the literature review section has been underlined how the increase in frequency and intensity of summer droughts are expected to be the most impacting phenomenon for the wellness of wetlands ecosystems. Since the MLW parameter (mean low groundwater) is calculated starting from the summer periods, and reflect the most dangerous situation, namely the lowering under tolerance and ideal conditions of groundwater levels, it is chosen for the comparison with the actual water level data estimated by the hydrological model, reported in the very next section.

The data from Niche model provided by INBO have the following structure:

Table 4 Niche Model Data

veg_type	*soil_name*	*MLW_min*	*MLW_max*	*inundation*
vn	K1	-0.82	-0.04	0, 1, 2
vn	KV	-0.62	-0.13	1, 2
vn	L1	-1.24	0.08	0, 1, 2
vn	LV	-0.62	-0.13	0, 1, 2
vn	V	-0.7	0.04	0, 1, 2
vn	ZV	-0.62	-0.13	0, 1, 2
hf	K1	-1.72	-0.42	0, 2
hf	KV	-1.72	-0.42	0, 2
hf	L1	-1.7	-0.21	0, 2
hf	LV	-1.7	-0.21	0, 2
hf	V	-0.87	0.2	0, 2
hf	ZV	-1.09	0.2	0, 2
mc	K1	-0.55	0.03	1, 2
mc	KV	-0.55	0.03	1, 2
mc	L1	-0.55	0.03	1, 2
mc	LV	-0.55	0.03	1, 2
mc	V	-0.45	0.03	1, 2
hc	K1	-0.68	-0.18	0, 2
hc	KV	-0.61	0.07	0, 2
hc	L1	-1.23	-0.15	0, 2
hc	LV	-1.17	-0.16	0, 2
hc	V	-0.81	0.19	0, 2
hc	Z1	-1.02	-0.46	0, 2
hc	Z2	-0.99	-0.51	0, 2
hc	ZV	-0.46	-0.23	0, 2
*hpr**	K1	-0.9	-0.52	1, 2
*hpr**	KV	-0.9	-0.52	1, 2
*hpr**	L1	-1.09	-0.35	1, 2
*hpr**	Z1	-0.9	-0.52	1, 2
*hpr**	Z2	-0.9	-0.52	1, 2
*hpr**	ZV	-0.9	-0.52	1, 2
hu	K1	-2.5	-0.5	0
hu	L1	-2.5	-0.5	0
hu	Z1	-2.5	-1.87	0
sf	K1	-1.72	-0.42	0, 2
sf	KV	-1.72	-0.42	0, 2
sf	L1	-1.7	-0.21	0, 2
sf	LV	-1.7	-0.21	0, 2
sf	V	-0.87	0.2	0, 2
sf	ZV	-1.09	0.2	0, 2

For each habitat, for each soil type in which it exists, is reported the parameter MLW, not as unique value but as a range between a maximum and minimum. Later in the description of the methodologies is explained how this range has been treated. The water levels are reported in meters, referred to the ground level. Negative values indicate groundwater, positive values waters above the ground level.

The last column shows the ideal inundation frequency for each habitat in a soil. More in detail:

- 0 means no flooding with river waters
- 1 means flooding more than one time in five years
- 2 means flooding less than one time in five years

As can be observe in the first row, certain habitats have multiple reference frequencies associated with them. Consequently, the most significant and reliable results are those pertaining to groundwater, where the data was more transparent and comprehensive.

A limit that has been encountered using the Niche Model concerns the match target habitat – soil type found in the data available from INBO and the match target habitat – soil type present in the shapefiles (*Figure 10*). In fact this, in addiction to the small number of habitats available from the Niche model, restrains the research.

3.2.3 The Hydrological Model

The following section is entirely referred to the Sigma Plan Report "Climate Robustness of the Sigma Plan", drafted by Professors and Ph.ds of the Hydraulics and Hydrology department of KU Leuven, who are cooperating with INBO in the Sigma Plan monitoring (*KlimaatrobuustheidSigmaplan-ConcepteindrapportKULeuven*, n.d.).

This chapter reports the characteristic of the hydrological model, from which are estimated the water levels in Kalkense Meersen, used for the comparison with the Niche model ideal ranges.

For simplicity, from now on when talking about this model it is referred to hydrological model, while Niche Model is the reference values one.

For each Sigma Area, a conceptual model has been developed to describe the average water level variation with a daily time scale. The model is based on the reservoir model concept, that describes the water volumes and the water heights for each Area. The model is a result of a combination of a hydrodynamic and a groundwater model created for the assessment of changed high water levels, changed groundwater levels, and changed precipitation runoff. For each area the model retrieves a timeseries, expressed in mTAW (see explanation of this unit of measure in section 3.3.1).

To calibrate the model were used available measurements of water levels in the specific areas, and the available simulation results of other hydrodynamics models. The model's simulation period goes from 01/01/1995 to 01/01/2023.

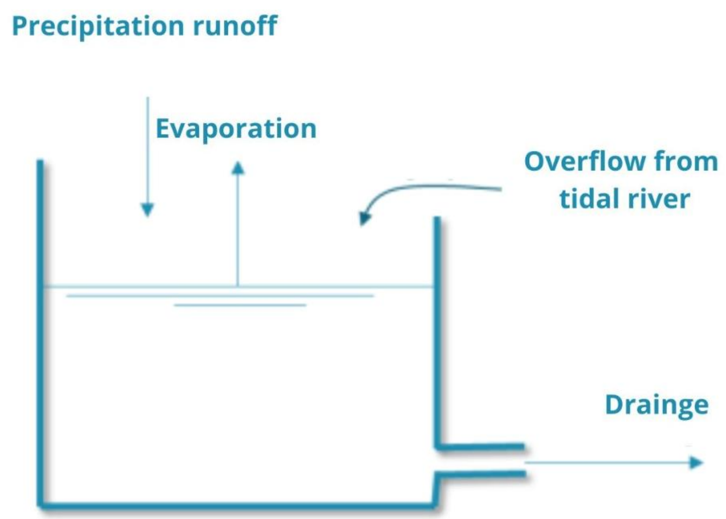

Figure 11 Graphic scheme of the conceptual model

As can be seen from the image, the conceptual model considers:

- The Precipitation, runoff and overflow from the tidal river as inputs
- Evaporation and drainage as output

The hydrological model runs for different scenarios, allowing multiple results analysis. In particular the data are available for:

- The current climate
- A future climate (2100 projection) in which no changed management actions is taken into account to contrast the effects of climate change on water fluctuations

- A future climate (2100 projection) in which a changed management is modelled, according to which the Culver pipe and the pumping are regulated to bring the conditions back to the current state.

As mentioned in the hydrological description of the study area, the management actions on the pipe can have a significant impact on the groundwater recharge. To a clear understanding of this, below is reported a schematic summary of the MLW retrieved from the timeseries for Kalkense for each scenario, representing the three average lowest summer groundwater levels over 5 years.

Table 5 MLW parameter for each scenario

Scenario	*MLW parameter*
Current climate	2,62 mTAW
Future climate with current management	2,30 mTAW
Future climate with changed management	2,57 mTAW

As can be seen, the current and future with changed management average summer groundwater level are extremely close.

3.2.4 Validation step

An important step of this work was the contribution for the validation of the groundwater model on which the overall hydrological model relies.

The simulated period of the groundwater model goes from 01/01/1995 to 31/12/2019, with a daily timestep. The model is a 2D grid-based system with a 250m resolution. It provides a macroscopic description of key hydrological processes for each grid cell. These processes include surface storage, surface runoff, infiltration, percolation, soil water storage, hypodermic runoff, drainage, groundwater storage, groundwater runoff, capillary rise, soil evaporation, crop evaporation, and transpiration (*KlimaatrobuustheidSigmaplan-ConcepteindrapportKULeuven*, n.d.).

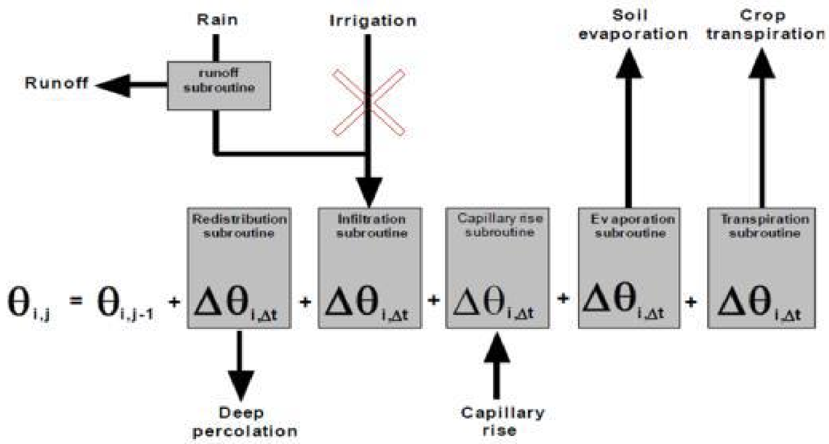

Figure 12 Graphic Scheme of the Groundwater model

The groundwater model produces time series of precipitation runoff and groundwater levels. The data are presented as a dataset of water levels, in which each column is an outlet along all the Sigma Plan's areas. To validate the model, its data have been compared with observed data acquired by the Flemish Watina database (INBO, n.d.).

To do so, through a GIS software the model's outlet were placed as close as possible to the available Watina's measurement stations. The data with their spatial information were passed to Python, which was able to retrieve the statistical relations within the modelled and observed values, along with graphical results. Below is reported an example of the validation's output for one outlet:

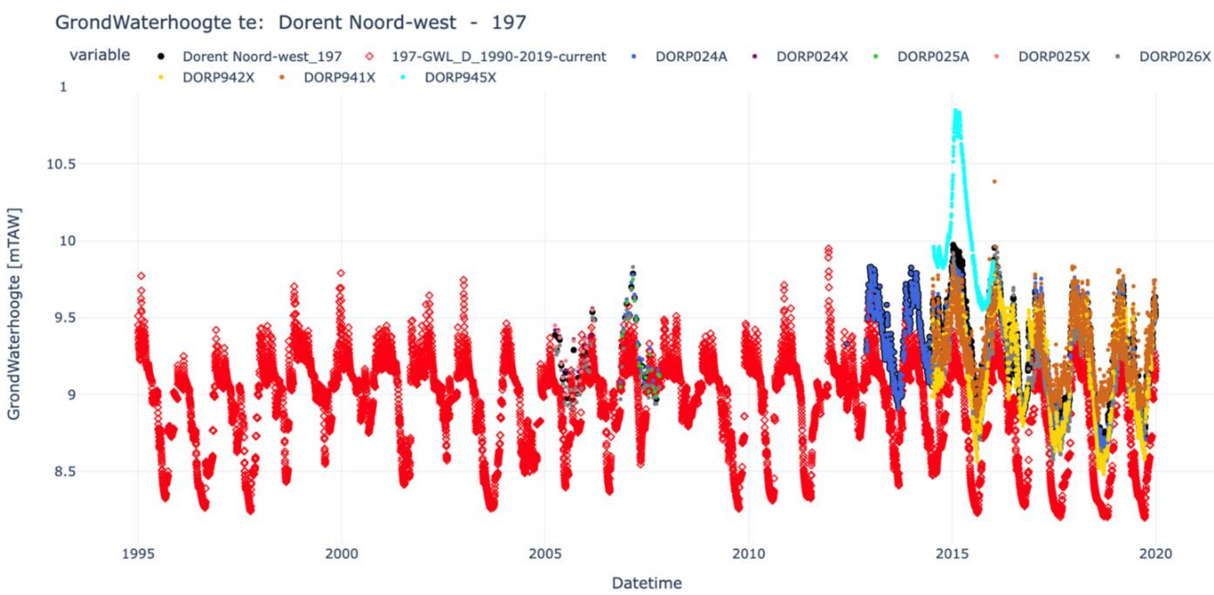

Figure 13 Observed and modelled timeseries comparison

This image shows in red the model data while the coloured points are the nearest Watina's measurement stations. The observed data are much less than the modelled, but except for the station "DORP945X" they all follow the trend of the model.

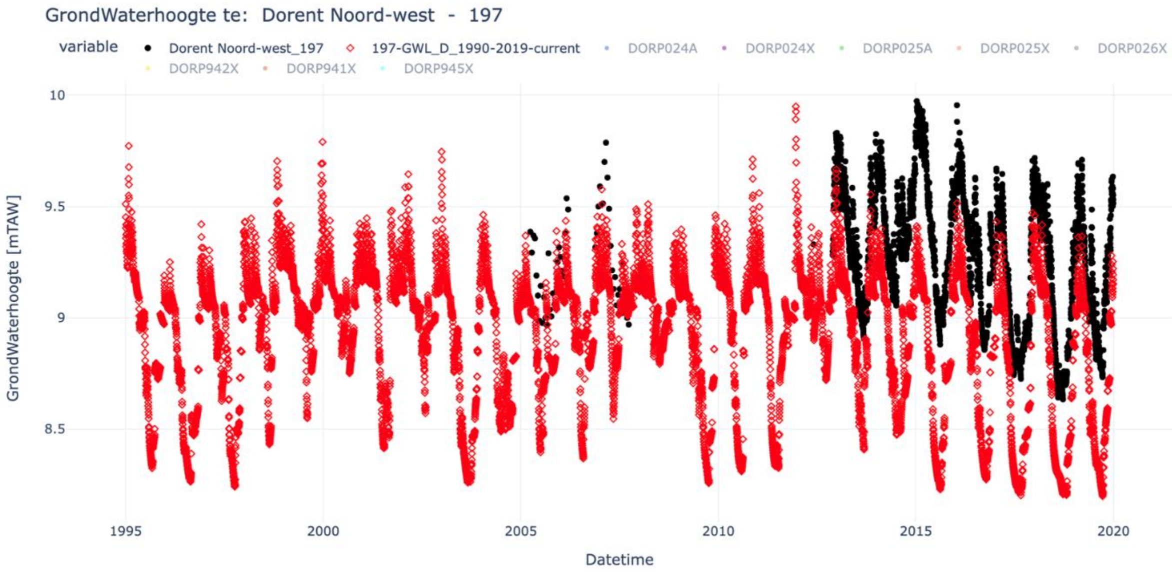

Figure 14 Averaged Observed and modelled timeseries comparison

This second image shows the mean value of the Watina station's data, compared with the trend of the model.

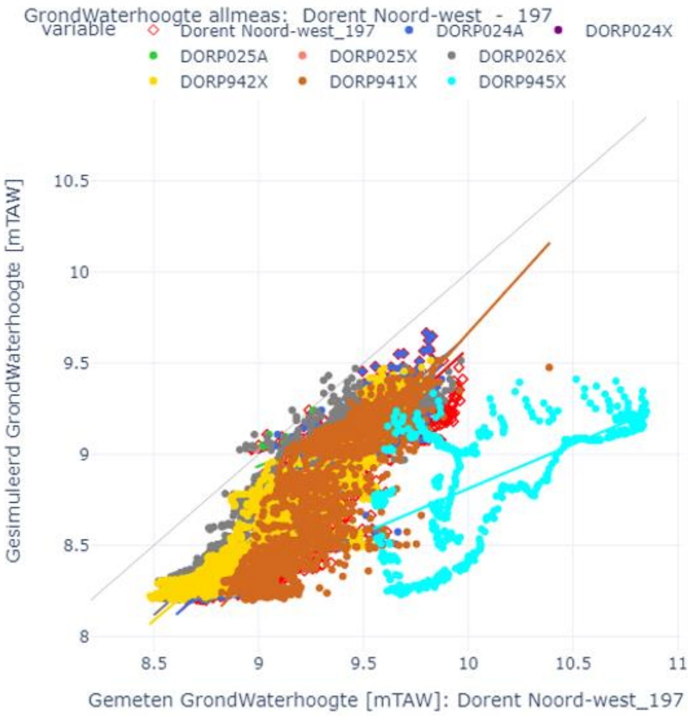

Figure 15 Spread of the observed and modelled data around the bisector

From this outcome instead is possible to see the distribution along a bisector of the model and the stations data. Again, the outlier is clearly visible.

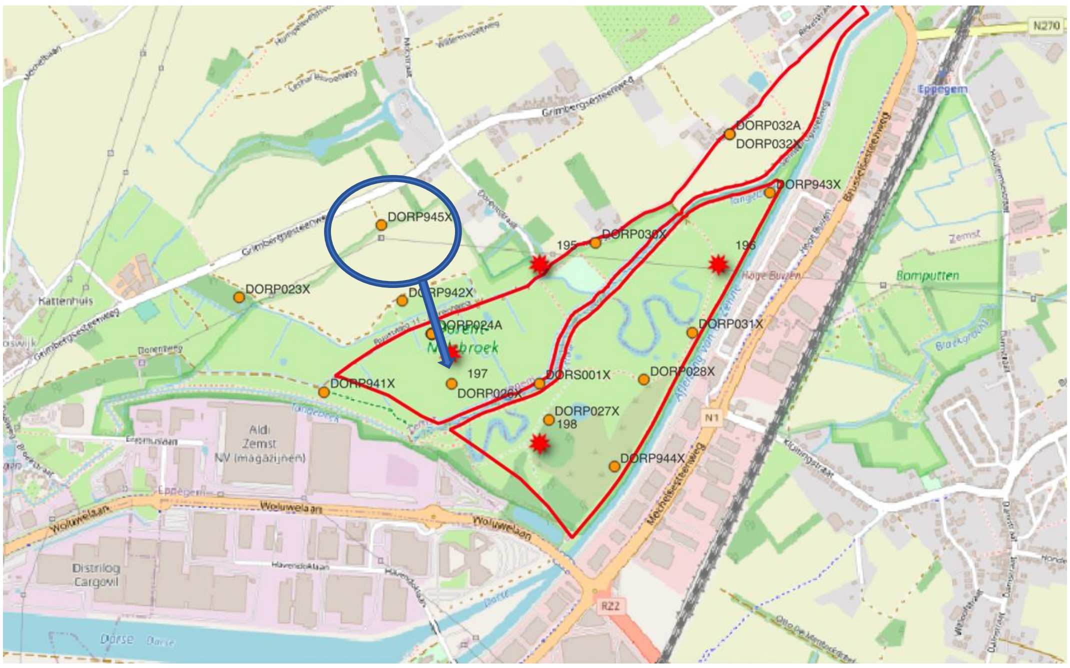

Figure 16 Spatial view of the stations and the outlet

This last image represents a spatial view of the outlets (represented with a star) and the Watina stations (orange dots). For this example, the outlier results could be due to an excessive distance of the station from the outlet.

3.3 Methods

In this section will be described the methodologies applied to the hydrological data in order to investigate the states of the habitats in the current conditions and future conditions under the effects of climate change.

The methodologies applied are of different types, for the groundwater and for inundation waters, and they retrieved different kind of results, that will be reported later in the next chapter.

The methodologies have the objective of comparing the ideal conditions of water level described by the Niche model and the actual conditions estimated by the hydrological model, by means of the parameter of low waters and inundation’s frequency described above, indicating the average summer groundwater level, and the inundation frequency.

3.3.1 First groundwater method

The first method compares the modelled water levels data with the range of low waters provided by the Niche model, namely MLW minimum and MLW maximum. These two values represent the range of low waters, calculated in the summer period, in which the vegetation inside the habitats can sustain and thrive in optimal conditions.

Looking first at the general terms, for this method the comparison is carried out between the low water ranges of the Niche model, and the interquartile ranges (first and third) of the water levels timeseries estimated by the hydrological model, for every target habitat that is at the same time analysed by the Niche model and that is found in the same soil type as modelled by the Niche model.

The interquartile range represents the spread of the data around the mean value (Casella et al., n.d.). It is calculated by subtracting the third quartile minus the first quartile, called also 75th and 25th percentiles. They represent respectively the values under which the 75% and 25% of the data inside an ordered dataset have a lower value.

In this way the objective is to check whether the central range of the water levels are included in the ideal range, only considering the values around the mean, and excluding the outliers. The methodology can now be explained in a more detailed manner.

Due to the high number of data and pixels, a python script was created. First, for every pixel in the map, through the GIS software it was retrieved the mean elevation of its area, according to a Belgian reference frame (Belgian Lambert 72). For doing this step an additional layer was used, in particular a DTM (raster) layer of elevation of the Sigma Plan areas. This was necessary since the hydrological model data were expressed in meters TAW as unit of measure; TAW stands for Tweede Algemene Waterpassing and is the reference height for measuring water levels in Belgium, about 2.3 m below mean sea (Vandenbohede et al., 2008). By subtracting by each data of the time series of water levels of Kalkense the mean elevation of the pixel, it was possible to find its actual water column height. If the value is positive, it is referred to flow waters, if it is negative, it is groundwater.

Using this script for simplicity, for every pixel in the map that is located in correspondence of a target habitat analysed by the Niche model and matched with the same soil according to the Flemish soil layer as the Niche model, then all the water levels of the Kalkense time series are subtracted by the mean elevation of the pixel and the quartiles of the new times series are calculated, the first and the third. After this the next step of the scripts consists in comparing the two quartiles, which now represent the values of references for the hydrological model, with the two parameters of low water of the Niche models, which are its values of references.

The code for each pixels retrieves a value from 1 to 5 according to different scenarios found as a result of this iteration:

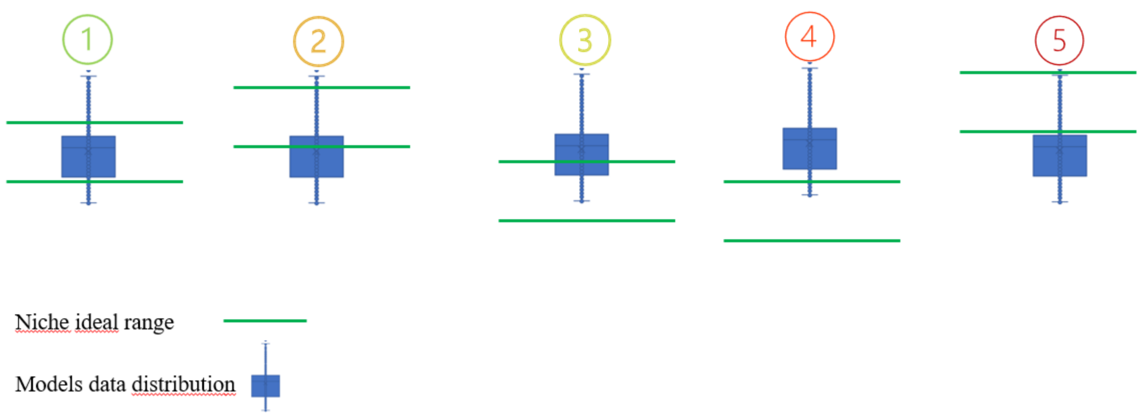

Figure 17 Schematic visualization of the code assigned to each pixel with the first method.

This image represents schematically the number that is associated with every pixel according to different scenarios. In fact, the interquartile range can be easily visualized through a box plot graph, called also box and whisker plot. The upper and lower segments of the central box in the graph represent respectively the third and the first quartiles of the modelled data, while the green segments represent the Niche's ideal range:

- **1** is assigned to a pixel for which the hydrological model timeseries' quartiles lie inside the Niche low water levels range
- **2** is assigned when the hydrological model timeseries' quartiles are underestimated with respect to the ideal range
- **3** is assigned when the hydrological model timeseries' quartiles are overestimated with respect to the ideal range
- **4** is assigned when the hydrological model timeseries' quartiles are completely shifted down with respect to the ideal range
- **5** is assigned when the hydrological model timeseries' quartiles are completely shifted up with respect to the ideal range

This iteration is repeated for all the scenarios of the hydrological model, retrieving three different maps.

Below is reported a workflow that sums up the main passages of the first method:

STEP 1

The hydrological model water levels are transformed from mTAW to depth expressed in m, using the mean elevation of each pixel, taking into consideration the topography of the wetland

STEP 2

From the new timeseries obtained in STEP 1, are calculated the first and third quartiles of the data

STEP 3

The quartiles are compared with the idea range, and for each pixel is assigned a number according to different scenarios (*Figure 17*)

3.3.2 Second groundwater Method

For the second method, the analysis is again carried out pixel per pixel, with a resolution of 10 m. In this case the procedure is the following: from the timeseries showing the water levels of the Kalkense Meersen wetland, is calculated the MLW parameter as defined by the Niche Model directive, namely by averaging the three lowest groundwater levels for the last five years during the summer periods (1 April – 1 October).

This parameter is a unique value for the whole wetland expressed in mTAW, so again the topography must be taken into account. For each pixel, from the MLW expressed in mTAW is subtracted the mean elevation in order to obtain the depth of the average summer groundwater.

As said previously, the parameters of low summer waters showing ideal conditions defined by the Niche Model are two, a maximum and a minimum, representing a range. While for the first method is chosen to consider the whole range and compare it with the quartiles of the modelled data, in this case instead the comparison is only carried out with the lowest value of the range. This allows to be more conservative in comparing ideal and actual conditions of the water levels.

So, for the next step, for each pixel in which is found the same target habitat matched with the same soil type as in the Niche Model, from the ideal MLW minimum is subtracted the hydrological model's one. In this way is calculated the deviation between the ideal and actual conditions. The difference for each pixel will then represent a shade of colour on a GIS map, going towards the green when the actual low waters are above the minimum ideal level, yellowish when they are close to each other and so the different is almost zero, reddish when instead the actual is found below the ideal, representing a risk situation.

Also in this case, this iteration is repeated for all the scenarios of the hydrological model, retrieving three different maps.

Below is reported a workflow that sums up the main passages of the second method:

STEP 1

For the whole Kalkense area is calculate the MLW parameter as defined by the Niche Model for the different scenarios

STEP 2

For each pixel, from the MLW according to the different scenarios is subtracted the mean elevation, to retrieve the m of depth

STEP 3

For each pixel, the modelled MLW is subtracted from the MLW minimum ideal given by the Niche Model and a colour from green to red is assigned in the map

3.3.3 Optimization methods

Relatively to the second methodology, further investigations are reported. Numerical analysis has been computed to identify alternative potential water-management actions that could yield economic and ecological advantages, compared to the current condition.

1. *Minimization of the error between the ideal and actual MLW parameters*

   For this map, the purpose was the calculation of a new average summer groundwater level for the future scenario without any artificial management actions, to be compared with the level predicted by the model that takes into account a water management action against climate change. For doing this, a numerical analysis was computed. For each pixel the difference (deviation) between the ideal and modelled parameters was squared, and all the resulting values for all the wetland's area were summed. Through the excel instrument called "solver", the minimization of the sum was computed, by a modification of the MLW parameter for future scenario without water management, retrieving in this way a new one and so new groundwater level.

2. *Maximization of the pixels inside the ideal range*

   The colour green in the second method's maps only indicates that the MLW minimum is above the Niche's one. But as shown before, the ideal range of low water presents an upper limit as well. For this reason, attention should be put also on this upper threshold, checking whether for a pixel the average of the three lowest groundwater level in the summer periods is at the same time above the MLW minimum and below the MLW maximum. In this sense, a further MWL parameter was retrieved by maximizing, by means of the Excel solver instrument, the number of pixels whose MLW value lie inside the minimum and maximum of the Niche's parameters. In this way, it is expected that the great majority of all pixels will show a green shade.

3.3.4 Inundation Method

As it can be seen from *Table 4* (Niche model data), the data available from the Niche model presents an inundation parameter, showing the ideal frequency of flooding a habitat should be exposed to. The parameters' translation is:

- 0 means no flooding with river waters
- 1 means flooding more than one time in five years
- 2 means flooding less than one time in five years

Similarly as the previous methods, in this case for each pixel in which is found a target habitat with the same soil type as in the Niche model, the inundation frequency is calculated, and the code 0, 1 or 2 is assigned. In case of multiple index for the same habitat-soil, it is arbitrary chosen the most inundated case.

The code of each pixel is transferred to the GIS software, and the map is coloured in red in case of not matching of the Niche and hydrological model code, in green for the opposite case.

Chapter 4 - Results

In this chapter will be reported the results of the methodologies explained previously. The outcomes of the research are presented in the form of maps with different colours and legends. For each method, is assessed which habitat is for current, future and future with changed management scenarios under optimal conditions or is suffering due to the state of water levels. In this way, discussion and hydrological proposals can be assessed for Kalkense Meersen Wetland.

4.1 First groundwater method's results

After applying the first method to the target habitats shapefile, using as data the Niche model for the ideal ranges, and the hydrological model for **current climate** scenario as actual estimated values, this is the resulting map.

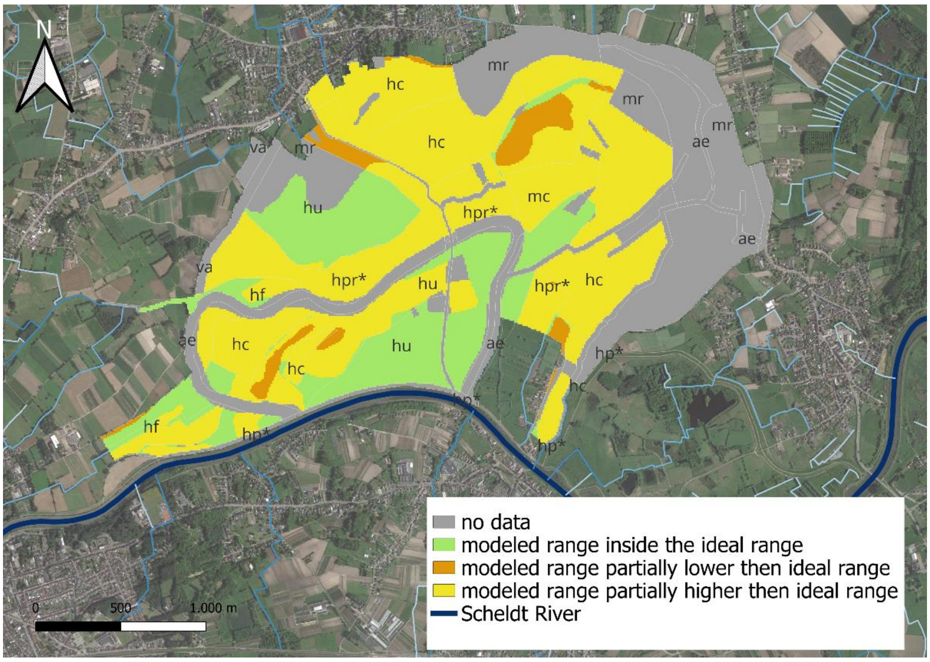

Figure 18 First method's result for current climate

As said previously, for each pixel is associated a number and consequently a colour. In particular:

- 1= green, model range is inside the ideal range
- 2=orange, model range is shifted down with respect to the ideal range
- 3=yellow, model range is shifted up with respect to the ideal range
- No data=grey, there was no match between the habitat-soil couple of the Niche model and the one found in the shapefile attribute table, or the target habitat is not included in the Niche model

The numbers 4 and 5 never appears in the map, meaning that the code nowhere found a pixel for which the interquartile range was completely shifted out from the ideal range, above or below.

The following map instead shows the results using the hydrological model for **future scenario and current management**.

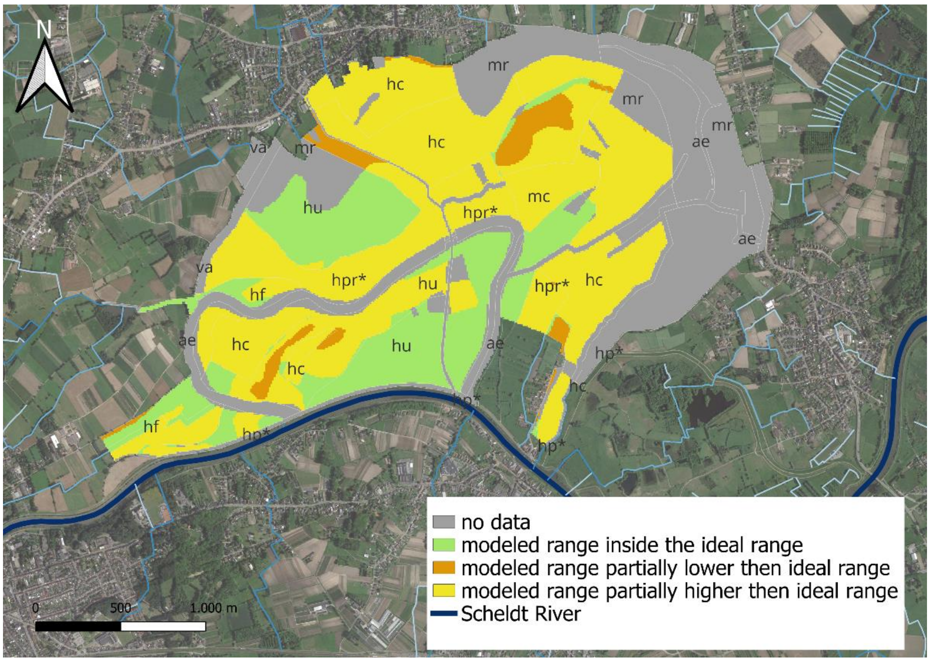

Figure 19 First method's result for future climate with current hydrological management

Lastly, for this map were used the hydrological model for **future scenario and future management**.

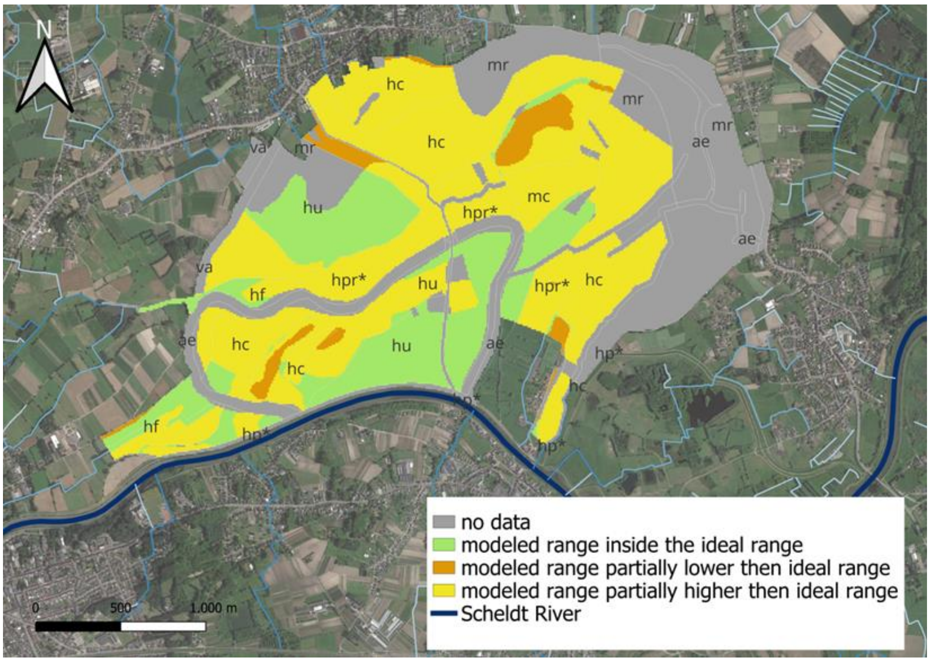

Figure 20 First method's result for future climate with changed hydrological management

Below are shown the relative frequencies of each target habitat for each category of number associated to the pixel. It is clear that hf and hu encounters the best conditions, and for the majority of the pixel there is a partial up shift of the actual range with respect to the ideal range, meaning that the modelled low waters are quite overestimated with respect to the ideal ones.

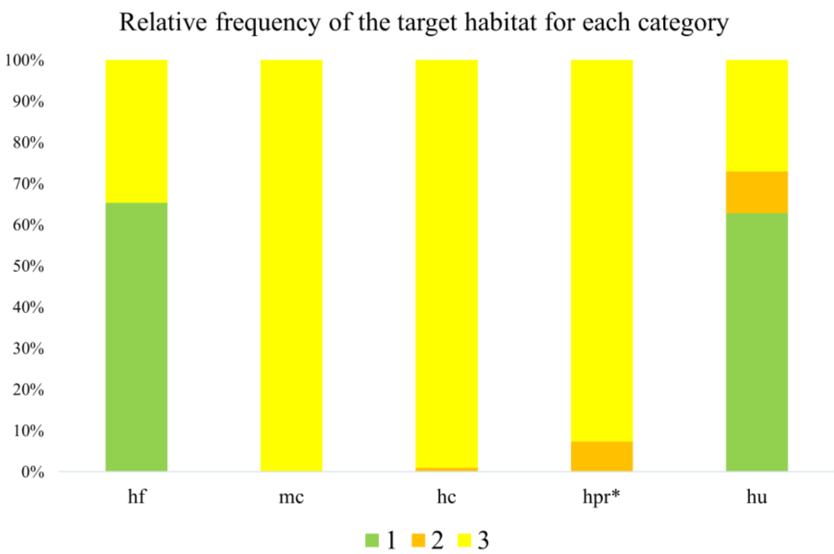

Figure 21 Relative frequency of each pixel's code

For the sake of completeness, for each habitat are reported the colours distribution for each soil type. In this way to a certain state is associated also the type of soil in which the habitat exists.

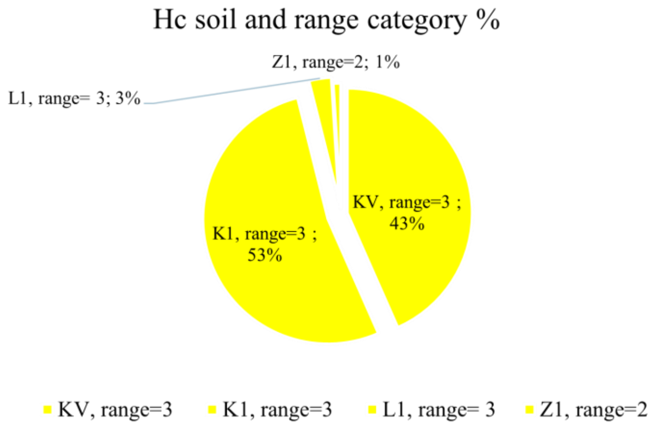

Figure 22 Soil type for each colour for habitat hc

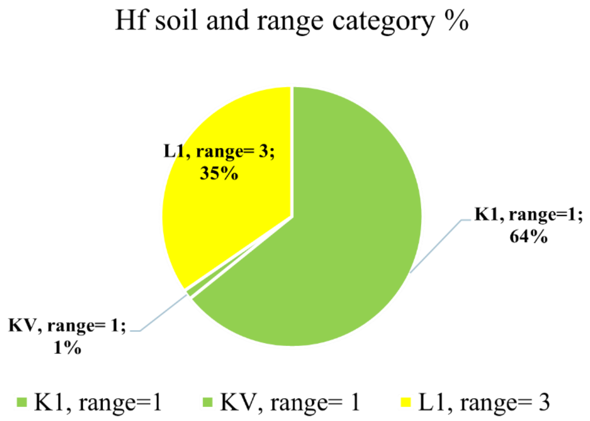

Figure 23 Soil type for each colour for habitat hf

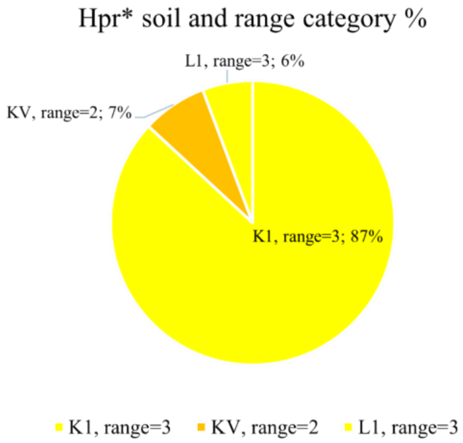

*Figure 24 Soil type for each colour for habitat hpr**

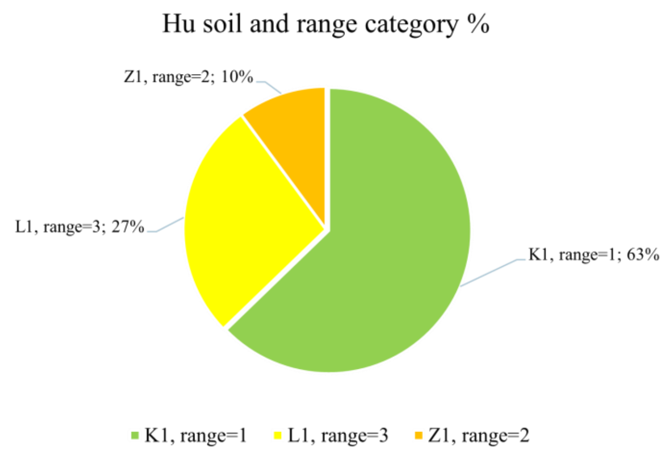

Figure 25 Soil type for each colour for habitat hu

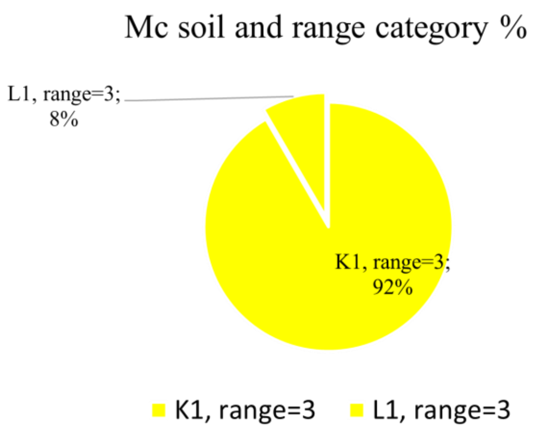

Figure 26 Soil type for each colour for habitat mc

Moreover, in the next graph are reported the frequency of occurrence of a certain habitat-soil type inside the Kalkense wetland. On the x axis is reported the number of pixels in which that match appears in the map, to give an idea of the distribution and frequency of the habitat-soil.

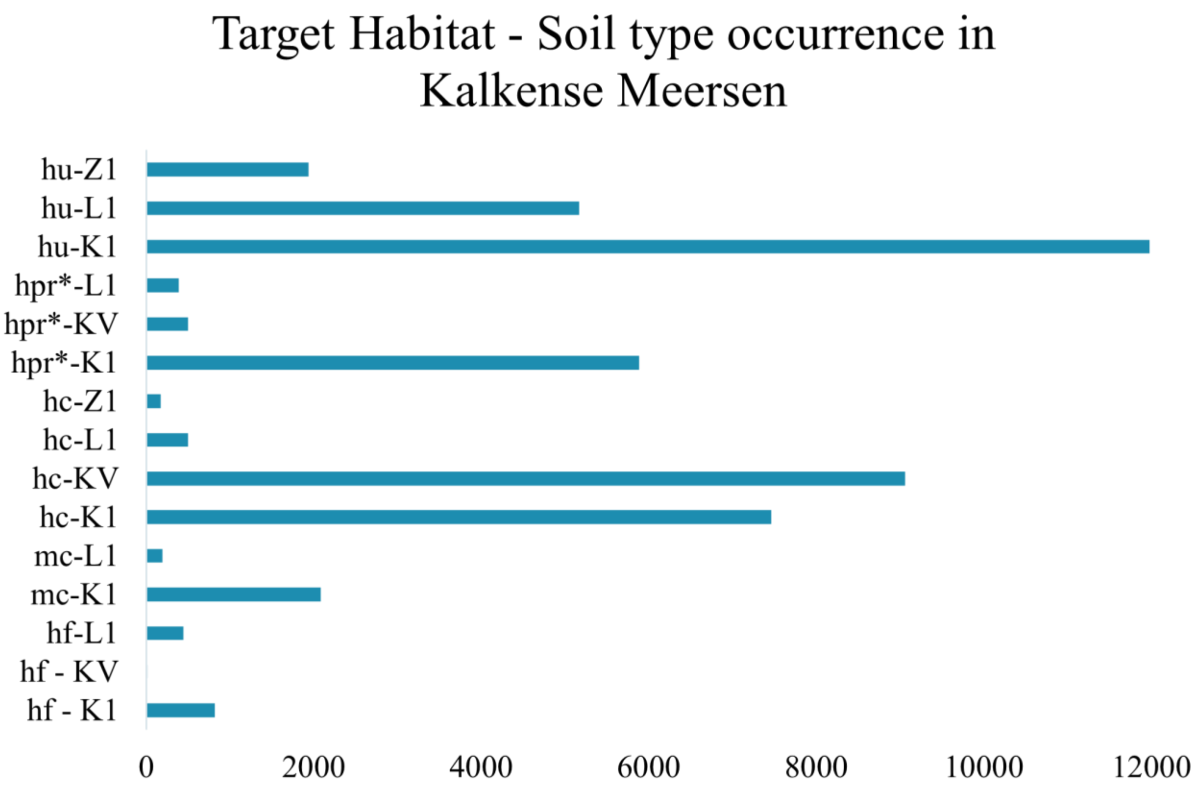

Figure 27 Target habitat - soil type frequency in the wetland

The habitat type hu (mesophilic hayfield) appears to be the most abundant associated with the soil K1 (sandy soil).

In a first moment, the methodology was applied also to the map showing all the current habitats present in the wetland, namely the biological valuation map updated to the year 2020. However, due to a lack of the data as discussed in previous chapters, the results reported below shows how the majority of the pixels are in this case classified as no data.

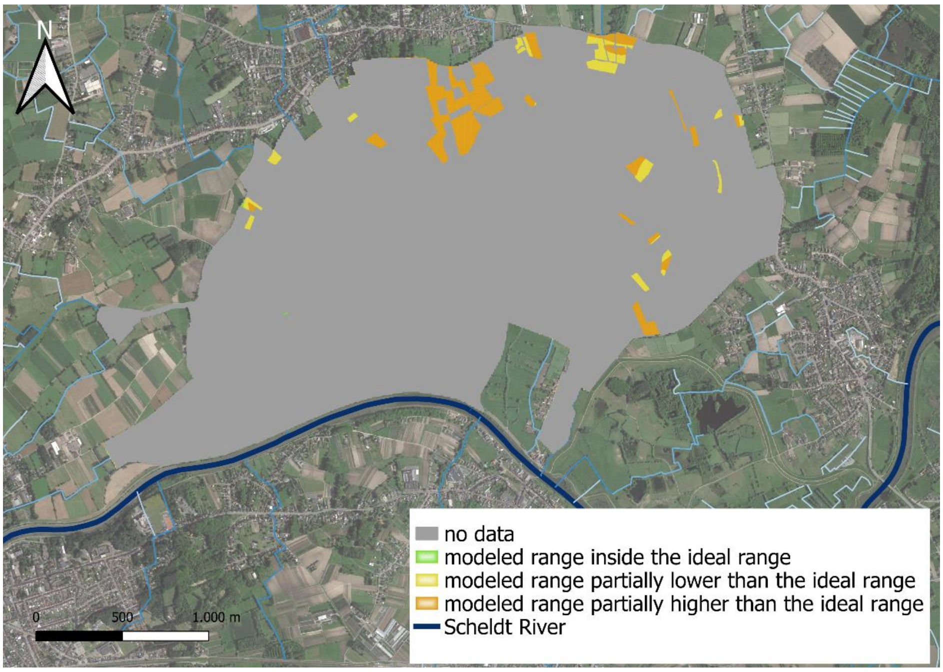

Figure 28 First method map with all the current habitats

The list of the current habitat is extremely higher with respect to those analysed within the Niche model, and therefore the output cannot be considered a meaningful result. Once again, the analysis focuses only on the target habitat listed by INBO.

See the Appendix B for the maps showing the results for BWK 1997, 2014, 2016, 2018.

4.2 Second groundwater method's results

In this section will be reported the resulting map according to the second methodology, in which the lowest groundwater in the summer period calculated for the hydrological model data is compared with the Niche's ideal lowest tolerable value.

Once again, the procedure is applied for all the three hydrological models, resulting in three different spatial maps.

The first map is referred to a comparison between the Niche model values and the hydrological model for **current climate scenario**.

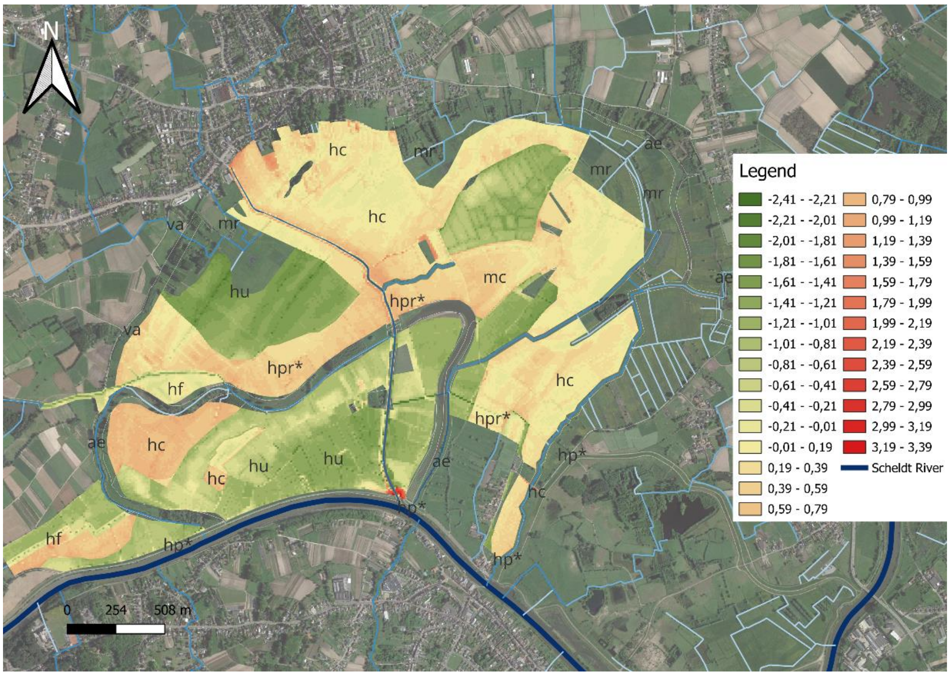

Figure 29 Second method result for current climate

The second map is referred to a comparison between the Niche model values and the hydrological model for **future climate without changed management**.

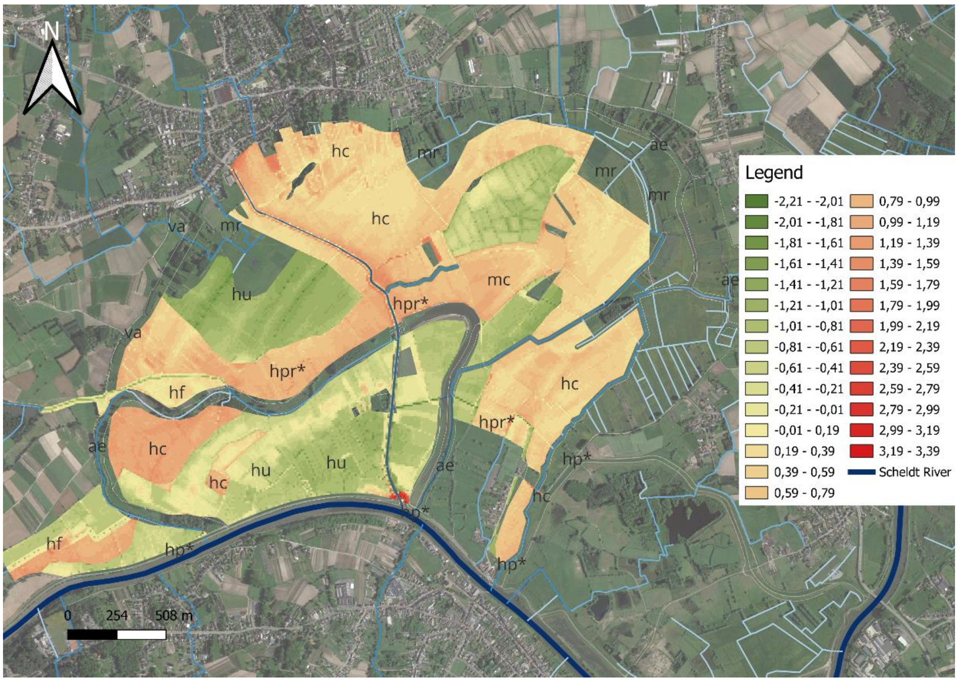

Figure 30 Second method result for future climate with current managment

The third map is referred to a comparison between the Niche model values and the hydrological model for **future climate with changed management**.

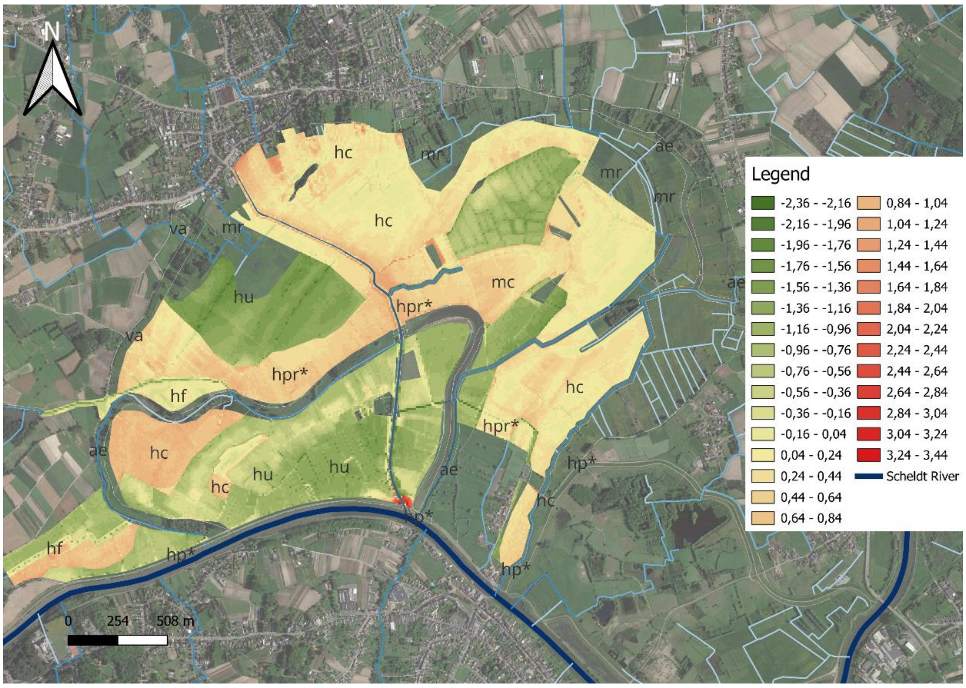

Figure 31 Second method result for future climate with changed management

The legend reported in the maps shows a gradient of colours from green to red, passing from a central part of yellow shades. To interpret the maps, is underlined that a pixel coloured with a green shade, is situated in a zone in which, according to the different scenarios, the MLW minimum parameter is above the ideal one. The yellow shade instead indicates that the two values are very similar, so the difference is close to zero, and finally a reddish shade indicates that the modelled low waters parameter lies below the ideal one, so the habitat is at risk.

4.3 Optimization maps

In this section are reported the results from the optimization methodologies.

Table 6 Comparison of the MLW parameters for each scenario

Scenario	*MLW parameter*
Current climate	2,62 mTAW
Future climate with current management	2,30 mTAW
Future climate with changed management	2,57 mTAW
Future climate with minimization of the error	2,39 mTAW
Future climate with maximized pixels inside the ideal range	3,09 mTAW

The table shows the summer average groundwater level found by the different scenarios and analysis. 2.39 mTAW is the value found when minimizing the difference between ideal and actual MLW minimum parameters in future climate without management, while a value of 3.09 mTAW assure that the maximum possible number of pixels lie inside the ideal range.

The first maps show what the situation would look like in case of a maximization of the number of pixels that lie exactly inside the MLW minimum and maximum range.

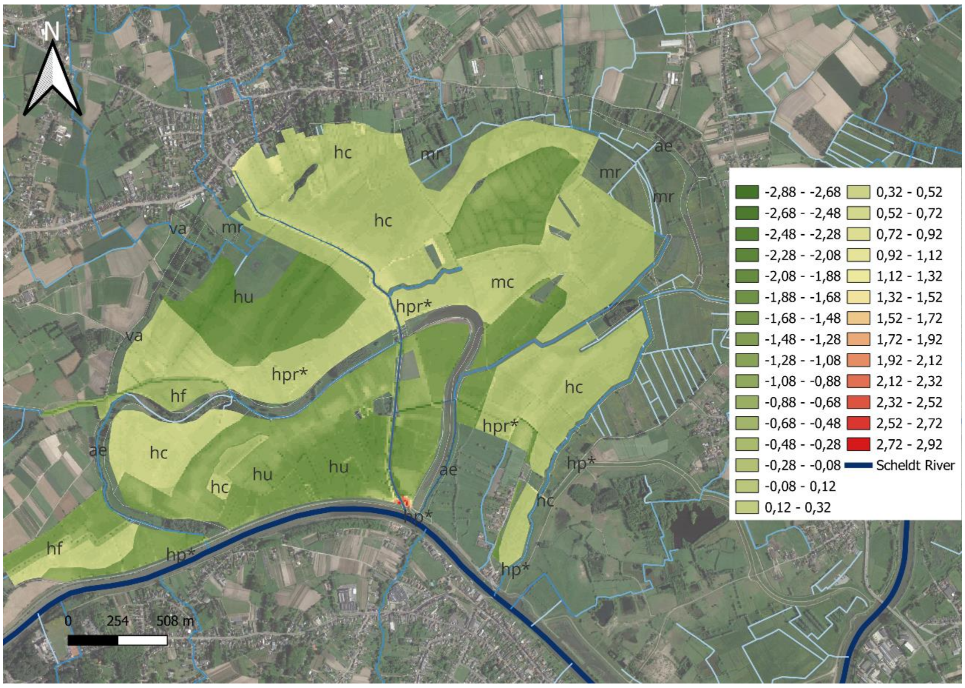

Figure 32 Resulting map with maximized number of pixels inside the ideal range

The second map shows what the situation in the wetland would look like after a minimization of the deviation between the water levels estimated by the hydrological model and the Niche model's ones.

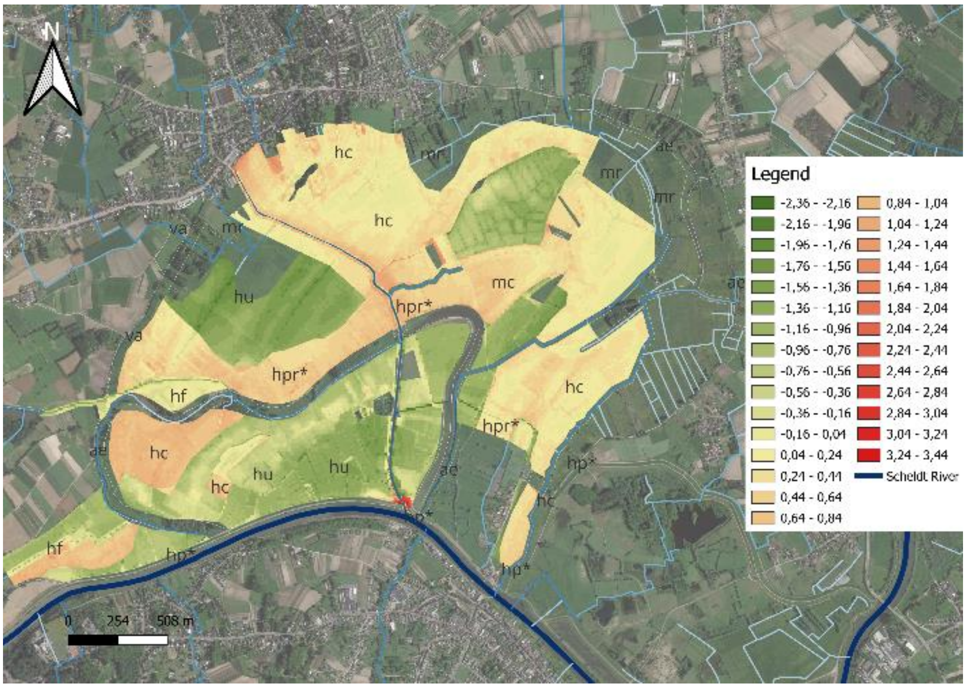

Figure 33 Resulting map with minimized difference between the ideal and actual MLW minimum parameter

4.4 Inundation method's results

In the last section of this chapter are reported the maps resulting after the application of the inundation method to the target habitat shapefile. In this case, the inundation frequency of the three models, namely how many times in the series the water levels were above the pixel mean elevation, were compared to the ideal inundation frequency provided by the Niche Model.

For every figure, on the left is reported the actual state of inundation, and on the right whether this rate is in line with the Niche one.

The first result is referred to the comparison between the Niche model values and the hydrological model for **current climate scenario**.

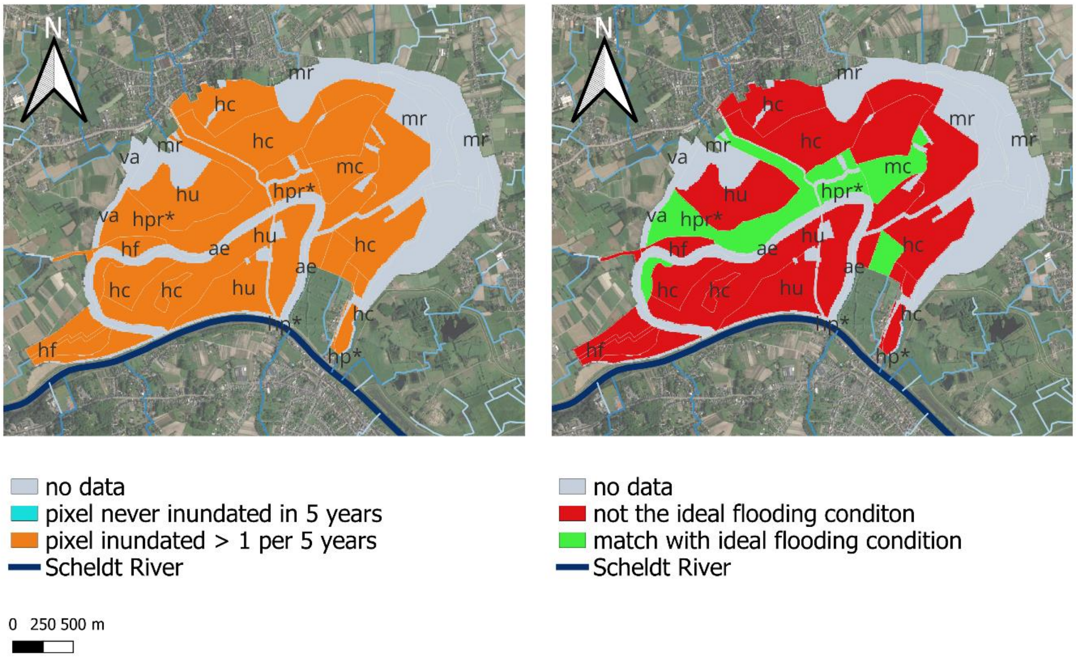

Figure 34 Result of the inundation method for current conditions

The second result is referred to the comparison between the Niche model values and the hydrological model for **future climate without changed management scenario**.

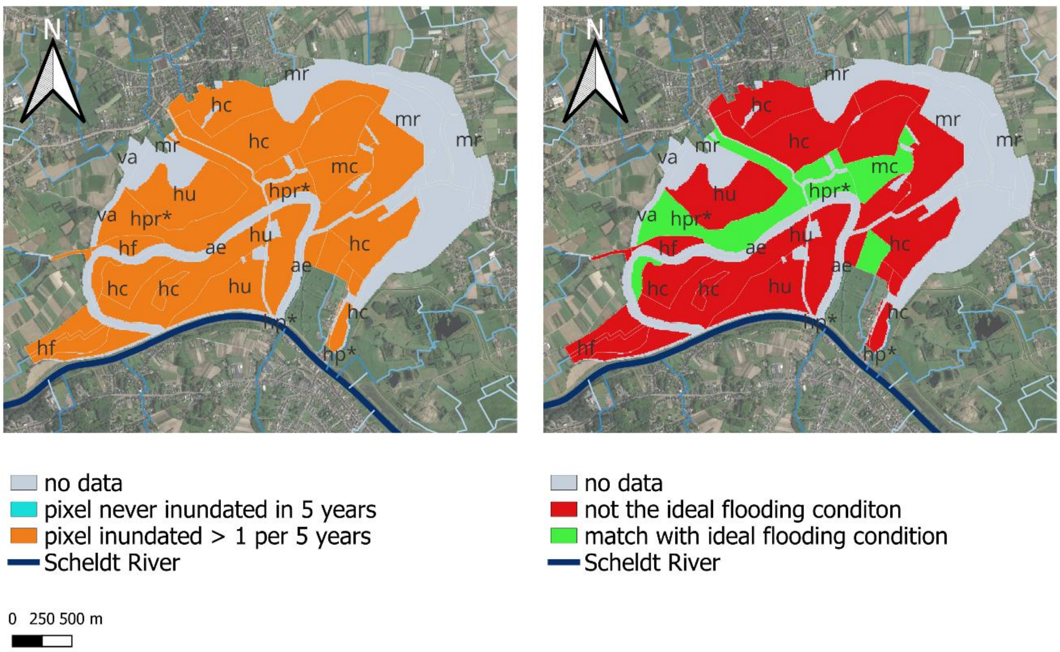

Figure 35 Result of the inundation method for future conditions in current management

The third result is referred to the comparison between the Niche model values and the hydrological model for **future climate with changed management scenario**.

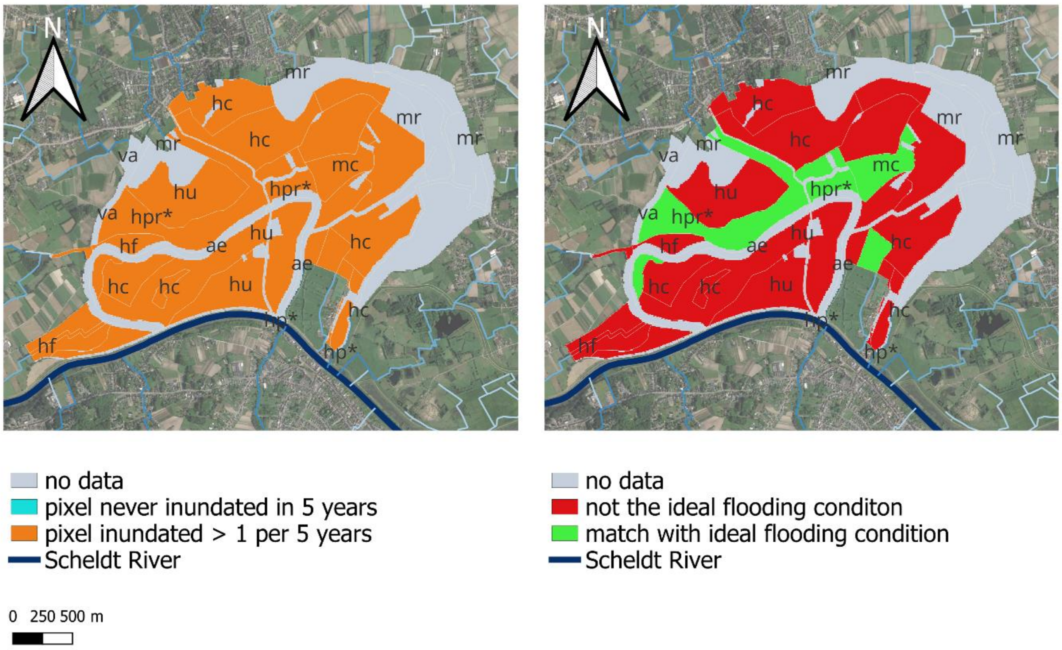

Figure 36 Result of the inundation method for future conditions and changed management

Similarly to the findings of the first method, also for the inundation clearly all the maps show the exact same results among the three models.

As anticipated before, according to the data acquired from the Niche Model, for the same habitat in a certain soil type, more than one parameter often was indicated, leading to a difficult interpretation of the data.

It was also not completely clear whether the way inundation was interpreted in this research, namely every time the water level was above mean elevation of the pixel, was in line with the Niche model interpretation. In fact, for lot of habitat-soil pair, a number 0 was associated by the Niche model, indicating that no flooding of river water should occur for the vegetation in that pixel. This was never found using the hydrological model, but rather always a parameter 1 (inundated more than once per 5 years) was associated to every pixel.

No indication of whether also the duration of the flooding time should be taken into account; in fact, some vegetation type might stand an occasion flood but not for prolonged time.

For these reasons these results will not be considered in the following further discussions.

Chapter 5 - Discussions

5.1 First method discussion

Looking at figures *18, 19, 20,* is clear that the three maps resulting from the first hydrological method for different climate scenarios are exactly the same. In other words, comparing the ideal Niche ranges with the quartiles of current, future with current management and future with future management conditions, the habitats response with respect to water levels doesn't change at all.

This result was investigated by comparing the three timeseries:

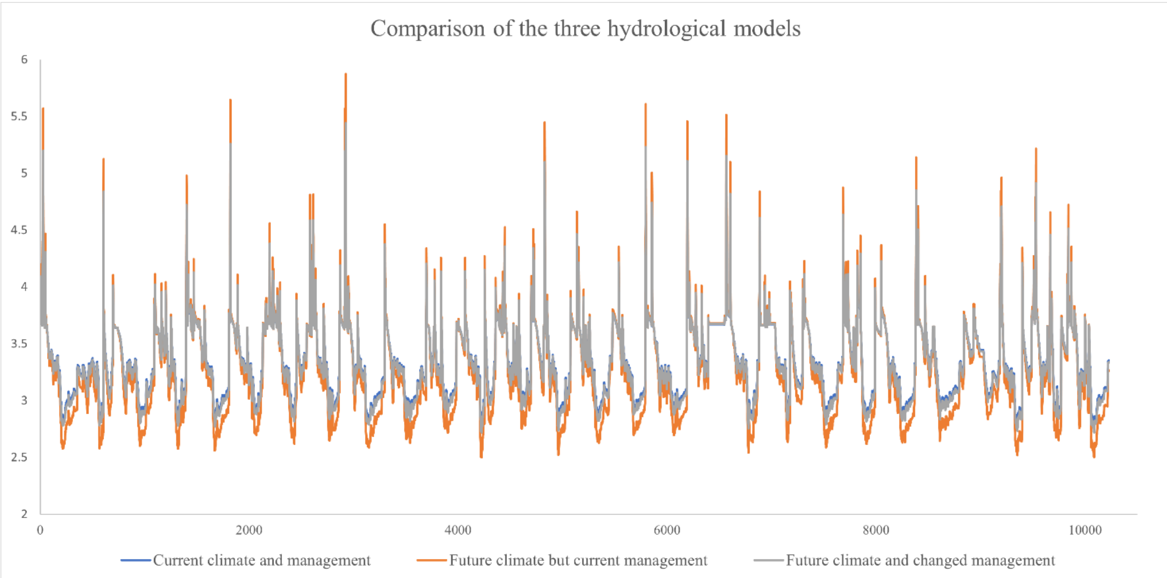

Figure 37 Comparison of the timeseries of the three scenarios

In the graph above are reported the timeseries of the three models, expressed in mTAW as unit of measure, to compare their trends.

The current and future with changed management scenarios are overlapped, since, as mentioned before, the future management are expected to bring back the conditions to the current state. Instead, for a future scenario without changed management is possible to appreciate a dropping of the low peaks during the summer months, as expected by many climatic models.

In addition, the first and third quartiles of each of the three timeseries were manually calculated.

Table 7 Quartiles comparison

Model:	*first quartile*	*third quartile*
Current climate and management	2.99	3.34
Future climate but current management	2.79	3.31
Future climate and changed management	2.95	3.35

The reason why with the interquartile methodology (first method), is not possible to see a change in the habitats' conditions between the current and the future scenarios, is to be searched on the fact that the quartiles of each series are very similar, and the type of approach doesn't highlight the effect of climate change.

5.2 Second method discussion

Through the second groundwater methodology instead, is possible to appreciate much more what are projected to be the influence of climate change on the target habitats. In fact, comparing the current climate with future climate without changed management against climate change is clearly visible a general increase of the red shades, and the green area in current scenario turns gradually in some point into yellow.

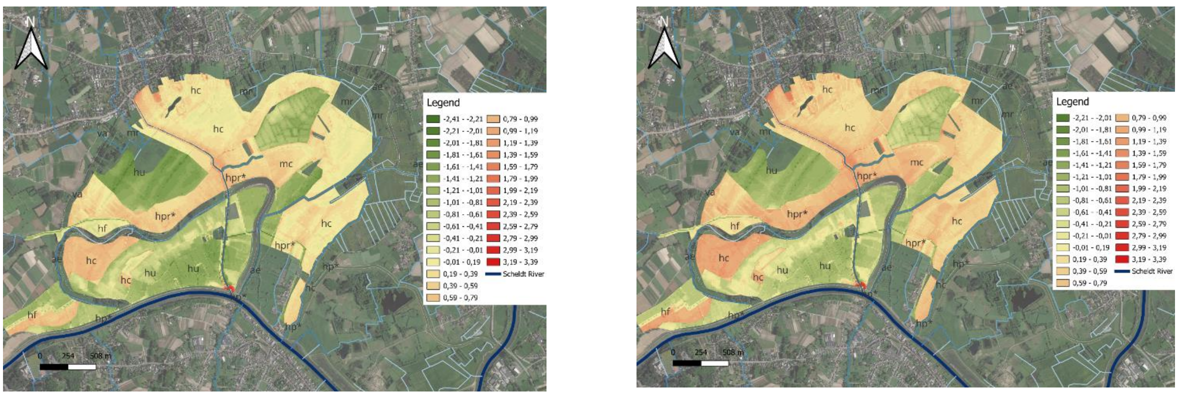

Figure 38 Current climate versus future climate without a changed management

Comparing the outcomes of the two different methodologies in future scenario they are concordant for what concerns the majority of green areas:

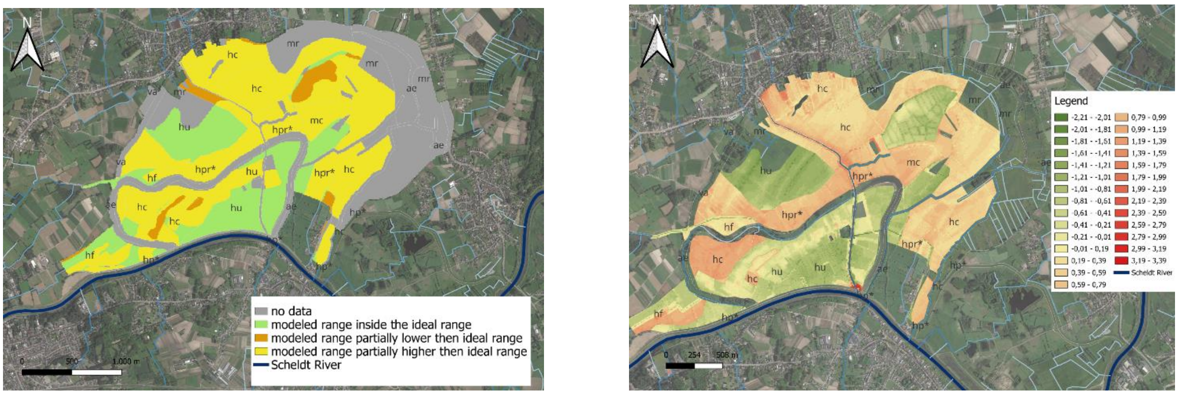

Figure 39 First method versus second in future scenario without changed management

Both maps agree on the safety of habitats hu (Mesophilic hayfield) and hf (Meadowsweet); over climate change these habitats are projected to remain in the green spectrum, just a little bit more toward the yellow, so closer to the lower limit. This is related to the fact that, among the target habitats analysed, they are those requiring the deepest MLW minimum as ideal lower groundwater level.

Table 8 Summary of the target habitats MLW parameters

Habitat	***MLW max***	***MLW min***
Hu	-0.5 m	-2.5m
Hc	-0.18m	-0.68m
Hpr*	-0.52m	-0.9m
Hf	-0.42m	-1.72m
Mc	0.03 m	-0.53m

This implies that, even with the estimated lowering of groundwater levels, the MLW is still above the critical one.

From *Figure 39* is then possible to see that the first method shows a rather optimistic outcome. In fact, around 50% of all the pixels is yellow, meaning that for many habitats for many soil types, the hydrological model's quartiles range is slightly above the ideal and critical one. The remaining pixels are around 33% orange, and 17% green. On the other side, the second method's outcome for current scenario shows the same percentage of green pixels, and the remaining pixels are for the vast majority very close or slightly above the lower idea value, while a few are found in a critical state. For future scenario without any changed management instead, the projections of the second method are definitely more pessimistic, with a clear increase of red pixels.

5.3 Optimization methods discussion

The maps generated through the second hydrological method clearly illustrate that, in the absence of any changed management strategy to contrast climate change, the anticipated scenario entails a significant decline in groundwater levels. This decline is so substantial that it would place the majority of the target habitats well below the safe threshold, signifying a critical condition.

These results are in line with the management actions projected for the Kalkense wetland by the authors of the Sigma Plan: "*In the Kalkense Meersen section, we will* ***elevate the groundwater level****, which will create an enormous, marshy grassland. The planned surface area of open water will be accomplished by reopening the old Scheldearm in the area.*" (Vlaamse overheid, n.d.-d).

The modelled hydrological managements for future scenario to contrast climate change described in Chapter 3, aim at this task. They foresee an adjustment of the exchange of water between the wetland and the Scheldt River through the Culvert pipe. By a trial process, the model adjusts the pipe's level that the water coming from upstream must overtop in order to flow into the river, so that it can be retained for as long as possible inside the wetland before flowing away into the river, leading to an increased drainage and recharge of the aquifers, and bringing back the current conditions. In this way the groundwater storage is increased to contrast the decreasing availability for the plants of water during the dry months. *Figure 29, 31* show the current and future with changed management results for the second method, and they are in fact almost the same map.

With the first optimization method that consisted in minimizing the difference between the Niche's and the hydrological model's summer groundwater average level in future scenario without management for every pixel, a very similar resulting map was obtained as the one for current climate, or for future climate with adjustment (look at *Figure 29, 33*). The MLW associated with this map is 2.39 mTAW. Since the minimization implies that the average summer groundwater level is found as close as possible to the lowest critical value, an ideal proposal could be a little higher value corresponding to 2.45 mTAW. With this groundwater level, is obtained the same result in terms of impact on the habitats as can be seen with a groundwater level of around 2.60 mTAW or 2.57 mTAW, as estimated by the current and the future with changed management scenarios.

Since the estimated summer groundwater level in future climate without changed management is 2.30 mTAW, with this further result of the research is reported that, potentially, with an adjustment of the Culvert pipe that leads to a recharge of 15 cm of the summer groundwater level, the resulting impacts on the vegetation are the same as with an increase of 30 cm. This result could eventually represent an economical advantage for the overall management plans, decreasing of more than 900000 m^3 the volume of water that has to be kept stored for prolonged time in the wetland. However, the analysis of the specific economic advantages is out of the scope of this thesis.

The second optimization method shows the best result among all the maps presented *(Figure 32).* In fact, thanks to the maximization of the number of pixels inside the optimal range, it is assured that not only as many pixels as possible are above the MLW minimum, but that they exist perfectly inside their required range of value. As expected from this procedure, the resulting average summer groundwater level is the highest among all the scenarios as can be seen from *Table 6*, translating in a map that is completely green (*Figure 32*). This resultant colour can be further discussed; in fact, since the second method in principle didn't consider any upper threshold for the comparison with the ideal value, but only the most critical and minimum one, one could have expected to find with this optimization method a spread yellow shade in the original dark green areas, due to a possible exceeding groundwater level above the maximum threshold. Instead, what came out was that the original green areas remained the same, while those previously red/yellow turned into a green shade. This indicates that with a summer level of around 2.60 mTAW some habitats, in particular those requiring really a low range, were already meeting optimal conditions, while rest of the habitats matched with a specific soil type were barely close to their lower MLW ideal required, resulting in pixels of yellow and red shadows. With an increase of 40 cm, leading to about 3.09 mTAW the summer groundwater level, all the habitats would potentially encounter not only the minimum ideal MLW, but also the maximum, existing in their optimal range. Finally, the second optimization methodology answers to one of the very first questions that arose at the beginning of this research. When first sharing ideas on the procedure to follow, one of the very initial proposals was to consider the current groundwater levels as ideal and compare them with the future one estimated with the models. But, at the same time, it was a hazard to consider the current conditions as ideal, without any reference value. The last map indeed showed that a higher summer groundwater level would represent a much better situation for the majority of the habitats with respect to the current conditions. However, elevating the groundwater to that level would represent a massive artificial hydrological management, and is not sure that the consequent outcome for the vegetation would be the same as the expected one. While an important elevation of the aquifer to the optimized level is theoretically the best scenario, additional research is required to determine whether this would indeed be the most effective real-world solution.

5.4 Comparison with literature findings

From *Figure 37* is clear that, as found largely on the literature, the hydrological model predicts for the future climate with no management for climate change a deepening of the groundwater availability for the target vegetation. The biological functioning of this vegetation, being classified as terrestrial groundwater dependent vegetation, would be highly impacted by a decrease of groundwater resource. Thus, the hydrological approaches reported in this work are a useful tool further exploitable by INBO to spatially visualize the response of the habitats to the water level fluctuations.

Similarly to the works of (Guareschi et al., 2020; Kingsford, 2011), in this research target habitats of high ecological value were the investigation target. According to the authors, to ensure the preservation of dominant plant populations, it becomes necessary to safeguard areas that are susceptible to environmental extremes, such as wetlands, and to focus on restoring the habitats structures, in this case by identifying management to the summer groundwater level in order to keep the habits within their ideal range.

The findings of (Staes et al., 2009) show that a river valley rewetting as restoration techniques would lead to groundwater recharge no matter which is the geographical position of the wetland inside the catchment. This could represent an effective solution for the Sigma Plan wetlands, in addition to the present management project for the area.

(Silvestri & Marani, 2013) used a mechanical approach to investigate the spatial distribution of salt marsh vegetation and analyse the conditions of the vegetation by its spread in certain areas. This thesis employs statistical conceptual model, but similarly to (Silvestri & Marani, 2013) the actual and predicted state of vegetation is assessed through the spatial maps, and according to the pixels' colours, is possible to visualize the state of the vegetation over different scenarios. As underlined by the authors, however, predictive models would be more useful for trace the evolution of a system. The same limit was encountered by the authors of the Niche model, thanks to which scenarios analysis are possible but the evolution of the vegetation in time, dictated by biotic interactions, is still not provided by the tool.

5.5 Proposals

As mentioned in the introduction, these methods were tested on Kalkense Meersen wetland as a pilot test, with the scope to give to INBO a tool replicable for all the Sigma Plan Areas.

Moreover, the information about the target habitats distribution available (*Figure 7*) originates from an assessment from INBO and the authors of the Sigma Plan about where to locate in an optimal way, in topographical and hydrological terms the target habitats. The map represents therefore a foresee of how the wetland should look like to maximize its ecological value.

Since the location of the habitats is a projection, a proposal of this work is to find a new proper location of each target habitat. More in detail, maps were retrieved placing one single target habitat at the time in the whole wetland starting from the Flemish soil shapefile, and applying the second method with the groundwater level obtained with future scenarios: 2.57 mTAW (future scenario with water management), 2.39 mTAW (future scenario with minimization of the error), 3.09 mTAW (future scenario with maximization of the pixels lying inside the range). Each map therefore will represent one singe habitat, and will show a greener shade where the habitats, according to the topography, groundwater level and scenario, would meet the best conditions.

In the maps some gaps of no data, represented by the non-coloured portions, are still present. They are linked to the habitat-soil match that must be respected for the comparison with Niche data. If in certain soil type of the Flemish map the target habitat is not found in the Niche model, then that portion of map will not be coloured.

Below are reported the results for the **future scenario with changed management (2.57mTAW)**. For the maps resulting from the other two future scenarios consult the Appendix C.

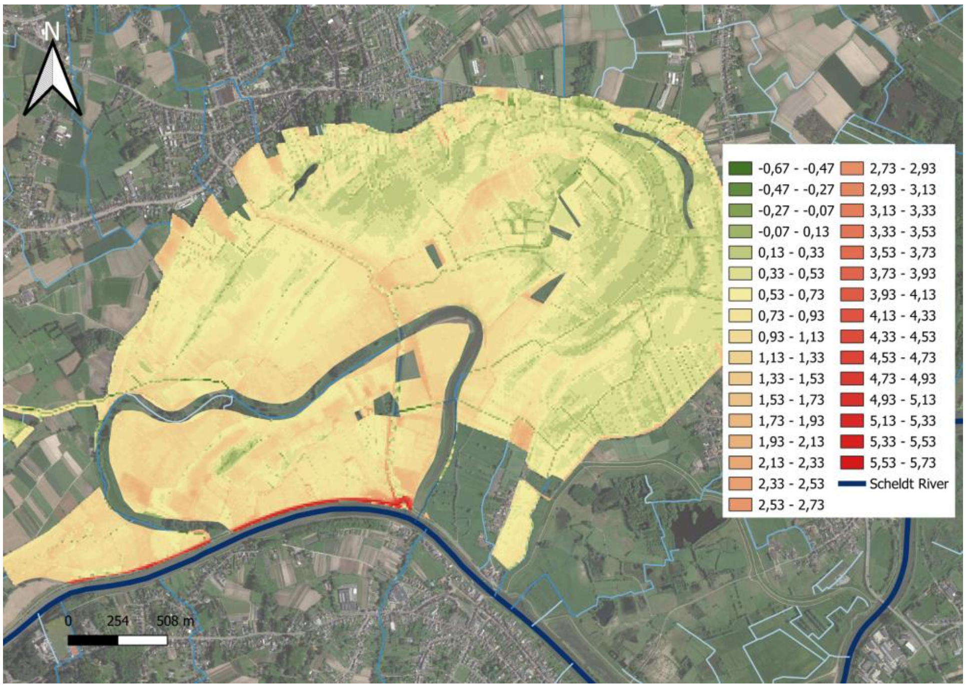

Figure 40 hc habitat

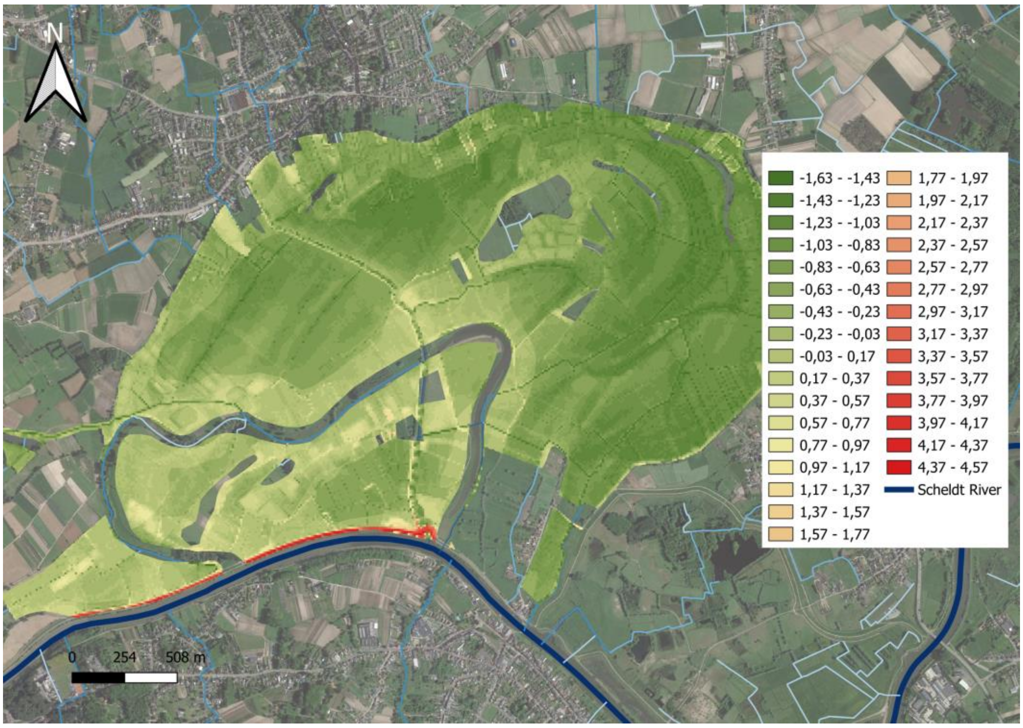

Figure 41 hf habitat

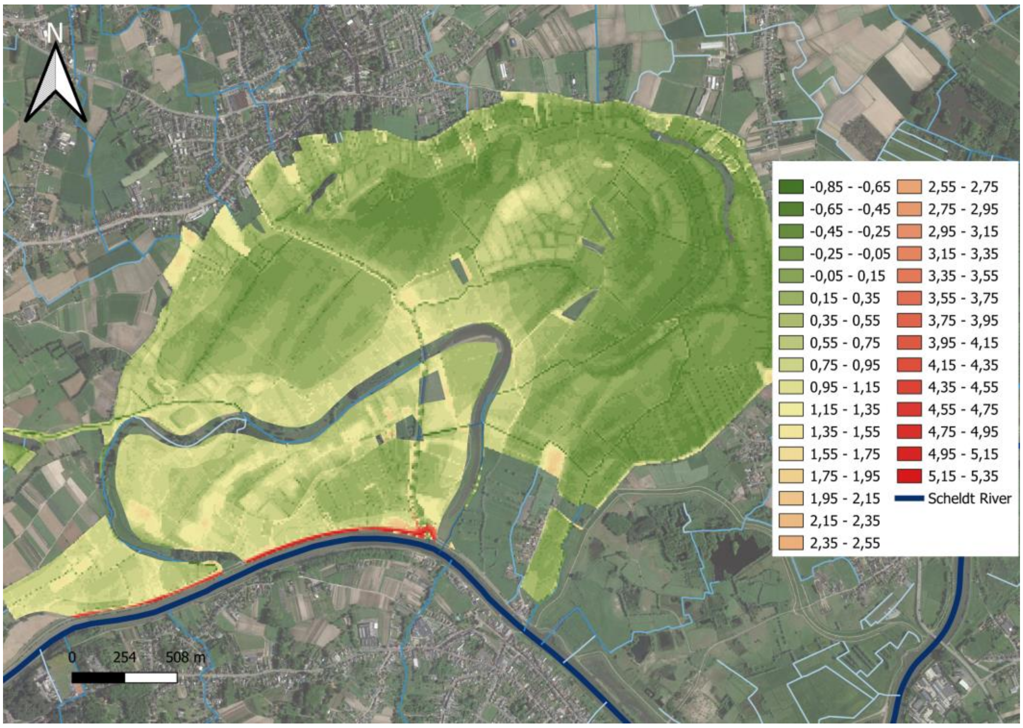

Figure 42 hpr habitat*

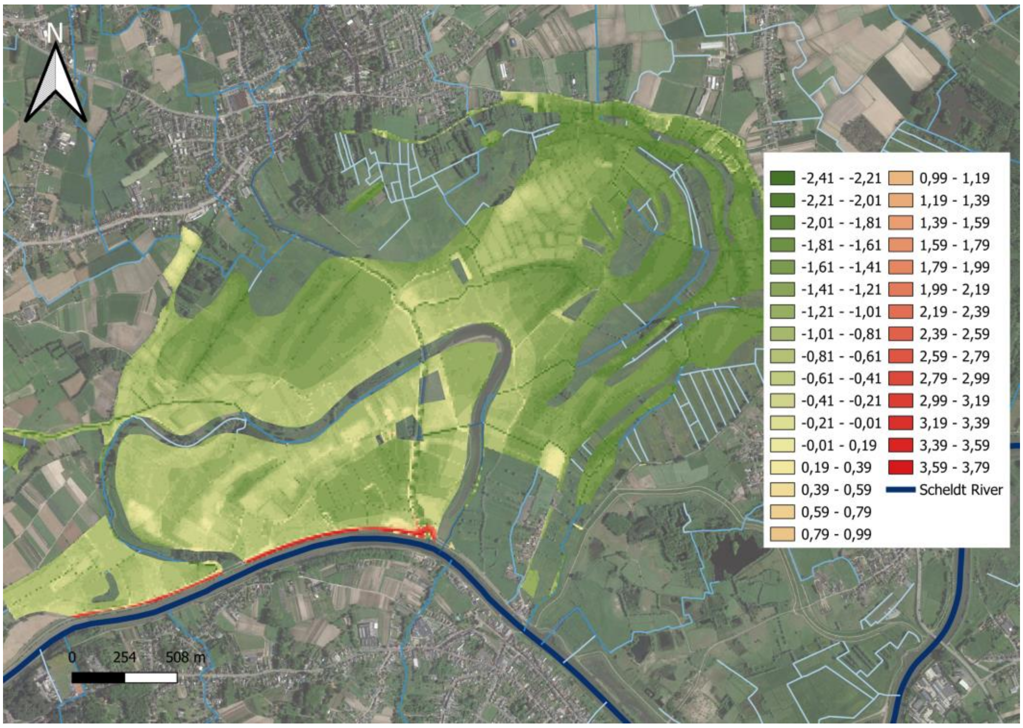

Figure 43 hu habitat

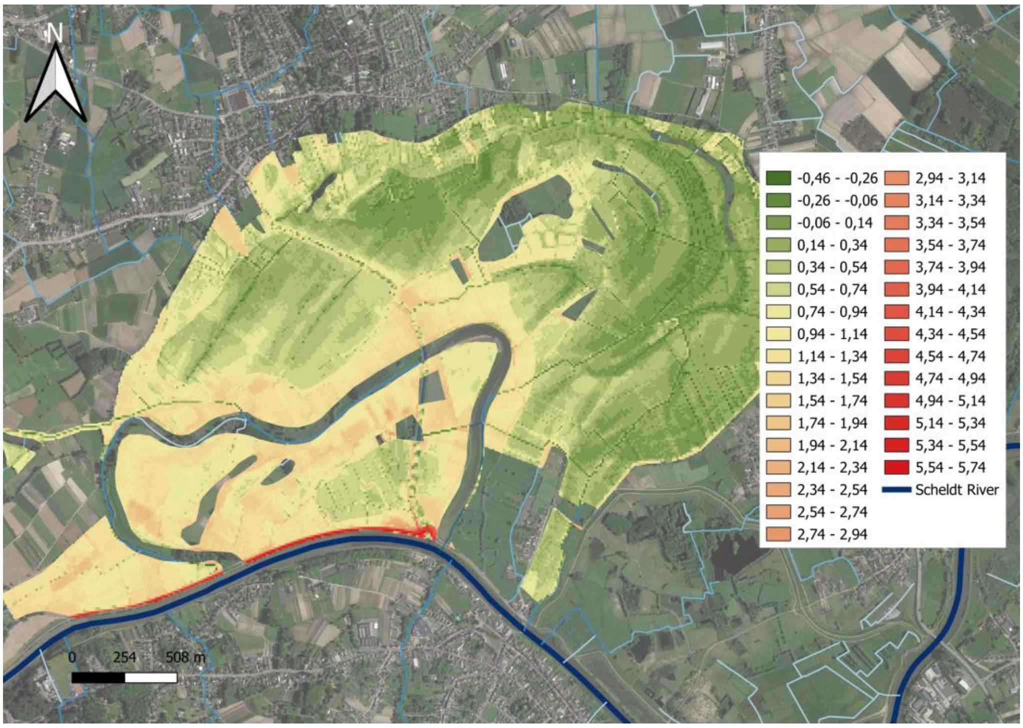

Figure 44 mc habitat

A recommendation that can be done for the research group that takes care of the eco-hydrological section of the wetland, could be to merge the results for each habitat in each scenario, making new target habitats maps. This can be done by a classification procedure, in which for a certain polygon extension, only the pixels up to a certain yellow/green threshold can eventually fit, while below that threshold they must be discarded. Doing a similar iteration, in each polygon with a certain soil type the procedure would show a list of which habitats could find the best conditions.

5.5 Limits of the research

In this section it is fundamental to underline that first of all this research assumes that the occurrence of valuable target vegetation inside its habitat is exclusively driven by the conditions of the groundwater and surface water levels, excluding all the other environmental conditions that make a habitat effectively inhabitable.

Another big limit that since the beginning put a restriction on the research was the small number of the habitats included in the Niche Model analysis. Each habitat moreover is associated with a specific soil type, and it happened in the research that the actual soil type encountered in the shapefiles for a target habitat was not the same as in the Niche reference model, leading to a decreased area of study.

Moreover, the investigations made on the effect of climate change on the vegetation is only restricted one abiotic factor, namely the groundwater level fluctuation, excluding therefore the whole biotic sphere.

Furthermore, any attempt to conduct an analysis comparing the current and ideal flooding frequency for each habitat was hindered by challenges in interpreting the available Niche data. Specifically, for a given habitat-soil combination, multiple inundation parameters were associated, and this ambiguity persisted throughout the duration of the analysis.

Finally, the research could have been enriched by reference value from the literature, indicating ideal conditions for each habitat type. In a first moment this approach was taken into account, however the literature offered insight of very few habitats among the listed ones, representing a less useful resource with respect to the Niche Model findings.

Chapter 6 - Conclusions

The materials, methodologies, and analysis presented in this study aimed to explore the potential effects of climate change on the valuable vegetation habitats within the wetland, designated by INBO. As suggested by prior researches highlighted in the literature review, an in-depth, habitat-specific analysis that considers local requirements can be instrumental in exploring effective adaptation strategies for biodiversity preservation (Guareschi et al., 2020; Kingsford, 2011). In fact, as stated by (Finlayson et al., 2017), climate change might result in species being unable to locate suitable environmental conditions (i.e., their habitat), or their tolerance limits being exceeded, making explorations of this type necessary.

In this context, when discussing adaptation strategies, it is referred to hydrological management plans designed to alter the summer mean groundwater table. The goal is to mitigate its decline, which can otherwise lead to the deterioration of habitat conditions (Sarkar et al., 2016).

The big questions at the principle of this research were step by step answered. Knowing in fact that the summer periods can be extremely dangerous for an ecosystem such as the wetland, that highly depend on the groundwater resources, it was imperative to investigate all the scenarios, current and future, of the hydrological models and their implications. In addition, further optimization prospectives have been considered.

The main findings of this research can be summarised as follows:

- Through the data from the hydrological model, it was indeed possible to understand how the target vegetation might develop under different climatic scenarios.
- According to a future scenario in which the hydrological managements of the wetland are not changed in order to contrast climate change, namely the management of the Culver pipe and the pumping of the water remains the same as the current, the result is a deterioration of the conditions for most of the target habitats. Many more red pixels show on the map, indicating that the mean summer groundwater level lies below their minimum required value.
- According to a future scenario in which the pumping of the water and the level of the Culvert pipe are managed to delay the runoff of the water from the wetland to the river as long as possible, leading to a major drainage into the wetland and a

replenishment of the groundwater, the conditions are brought back to those retrieved from the current model.

- According to a future scenarios in which a possible mean summer groundwater level is designated by a numerical analysis that minimizes the difference of the residuals between ideal and actual values, a mean groundwater level 15 cm lower than the modelled one could bring back the conditions to the current state, leading to economic advantages.
- Finally, according to a future scenario where the number of areas in which a habitat meets exactly its ideal range of low waters (MLW minimum-maximum) is maximized, increasing of about 40 cm the summer groundwater level of the current conditions, would potentially bring a massive ecological benefit for the target habitats. Given the significant artificial management of vegetation in this perspective, further research should be conducted to assess its actual effectiveness.

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Appendix A

Target habitats description

The following information are entire derived from the Ecopedia website (Ecopedia, n.d.) , and are a description of the target habitats inside the wetland analysed by the Niche Model.

1) *Habitat hc – Marigold grassland*

   The dominant species for this habitat highly depend on its location, and they span from woodrush to blueberry. The corresponding Natura 2000 codes are 2190 and 6410.

2) *Habitat hf – Meadowsweet*

   Hf habitat describes wet areas with meadowsweet, in which eventually also species of marsh marigold and reedland could be present. This habitat is autochthon in the Flemish region, and occurs mainly along ditches, streams or rivers. Usually, it appears as abandoned wet grassland. The vegetation inside this habitat develops optimally on moist nutrient-rich soils, while the sandy soil represents a less suitable habitat. Regarding the hydrological requirements, optimal growing sites are characterized by a high water table . According to (Ecopedia, n.d.) "*during the winter they are often flooded, in the summer the groundwater level drops several tens of centimetres below ground level. The typical species are therefore all groundwater dependent*". The corresponding Natura 2000 codes are 2190 and 6430.

3) *Habitat hpr* - species rich permanent cultivated grassland*

   This habitat involves a broad range of permanent grasslands, including comb grass, field barley, silverweed, large foxtail grassland, but also degraded semi-natural grasslands. The habitat is also characterized by the presence of a pronounced microrelief, such as a depression, or lanes, and canals or ditches. The corresponding Natura 2000 codes are 1310 and 1330.

4) *Habitat hu – mesophilic hayfield*

   This habitat includes hay meadows, but also roadside vegetation such as glossy oats of large foxtail. For this habitat the groundwater table is often permanently several meters below the ground level. In this group are present a great variety of different species, and most of them can be classified as groundwater dependent. The corresponding Natura 2000 codes are 6120, 6510, 2190. .

5) *Habitat mc – large sedge vegetation*

This habitat code stands for large sedge vegetation, that includes dense, low-growing and species poor communities. Sharp sedge, swamp sedge and bank sedge belong to this habitat. The typical soil in which this habitat occurs is a loam or clay soil, but also peat soil type. Regarding the hydrology : "*Relatively large fluctuations in the water level can occur, but the groundwater table never drops more than a few tens of centimetres below ground level in the summer . Long-term inundation is also necessary to maintain the vegetation type. The occurrence of large sedge vegetation is therefore limited to stream and river valleys*" (Ecopedia, n.d.). So, the habitat requires a rather shallow groundwater table. Large sedge vegetation is usually very productive, leading to the formation of thick layers of litter. The corresponding Natura 2000 codes is 2190.

Appendix B

Biological valuation maps 1997, 2014, 2016, 2018

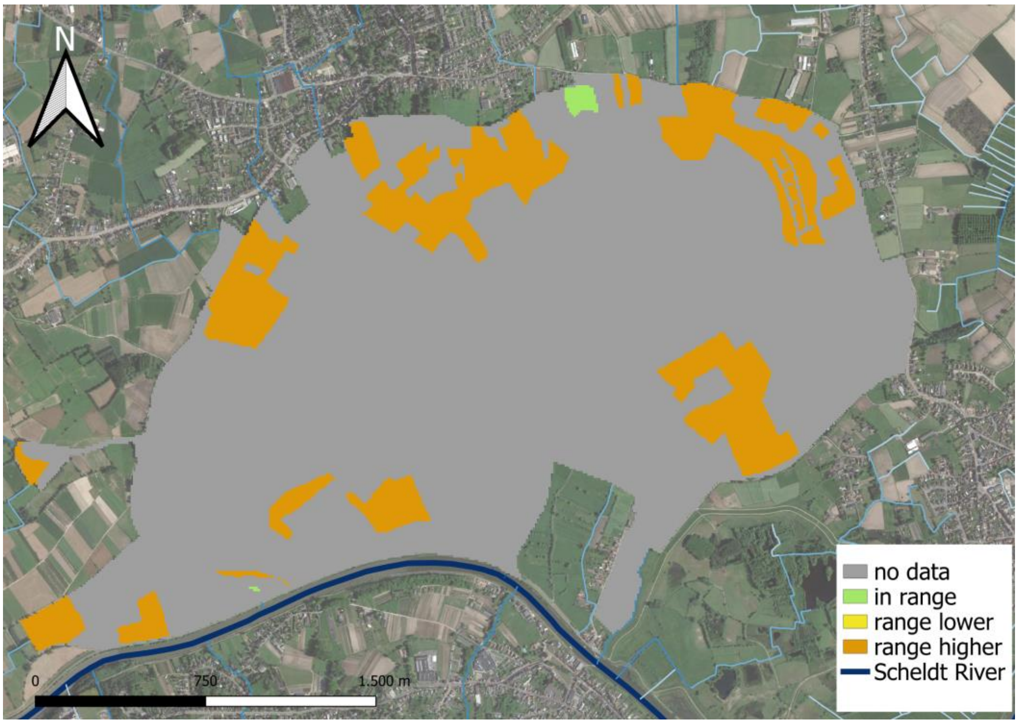

Figure 45 Biological Valuation Map 1997

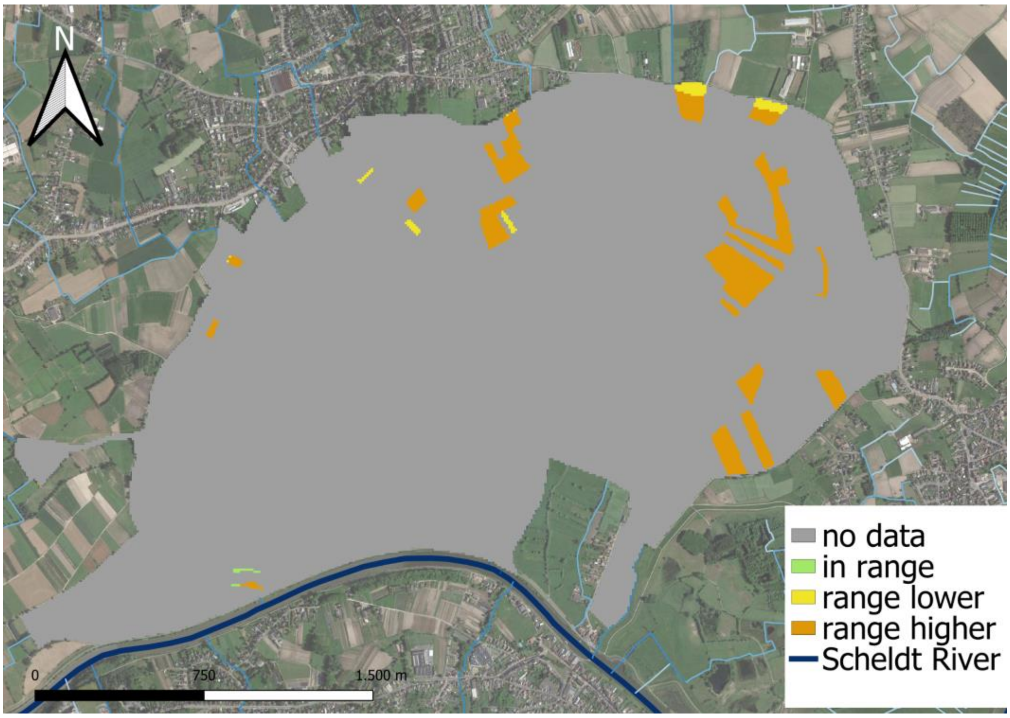

Figure 46 Biological Valuation Map 2014

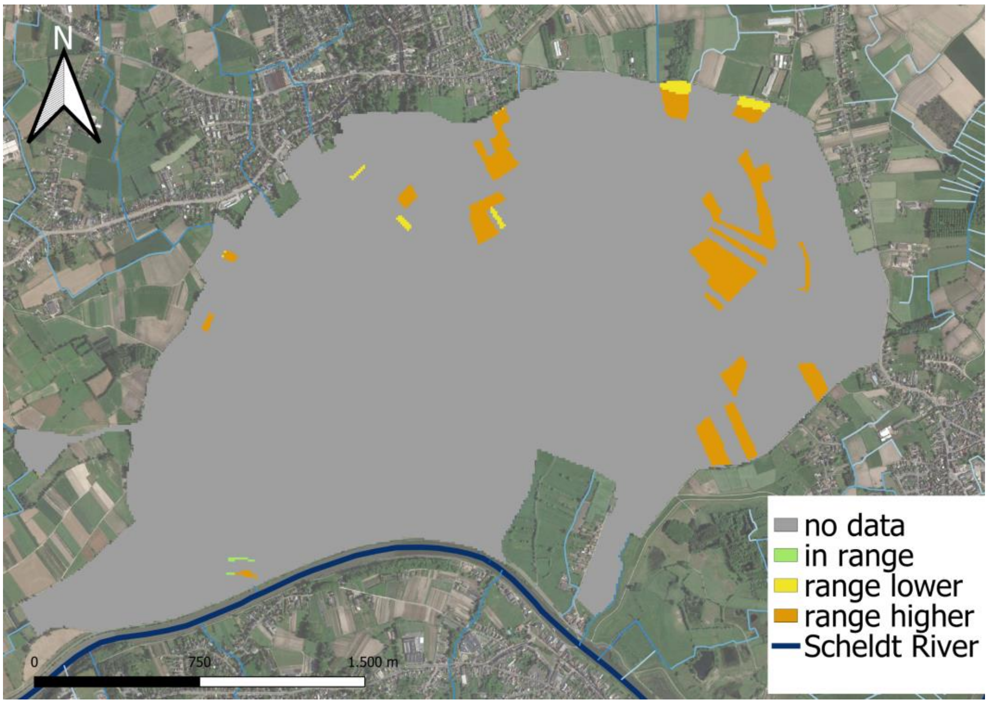

Figure 47 Biological Valuation Map 2016

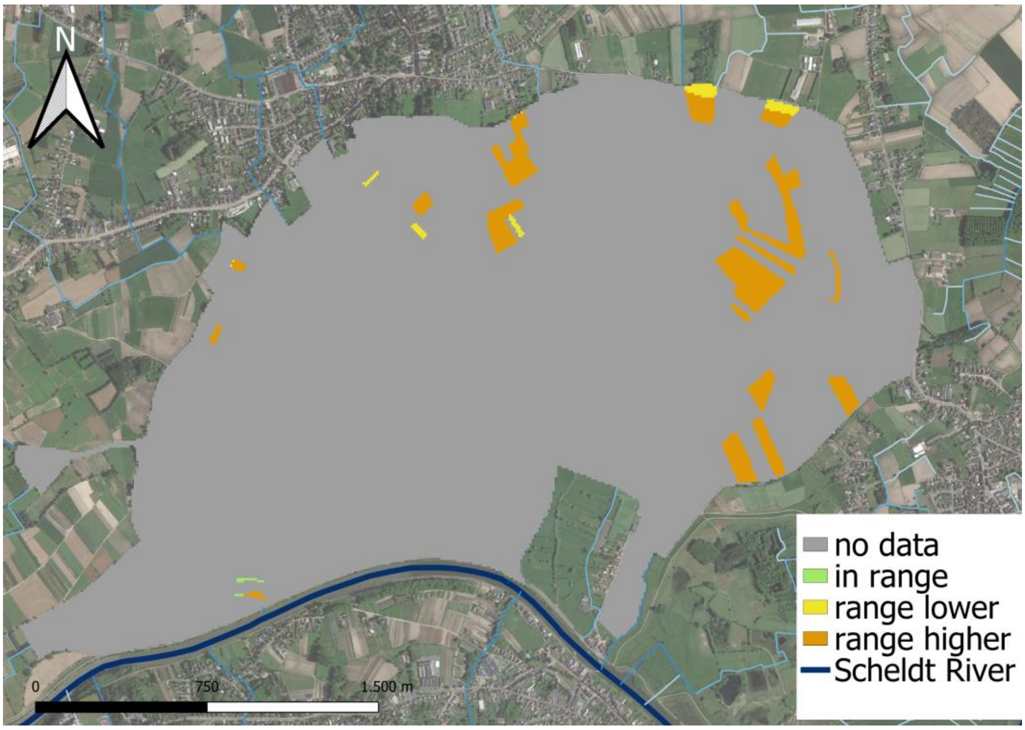

Figure 48 Biological Valuation Map 2018

Appendix C

Proposal with future scenarios

In this section of the appendix will be reported the maps discussed in the proposal section, showing the distribution of one habitat at the time for two future scenarios:

1) *Future scenario with minimized residuals (2.45 mTAW)*

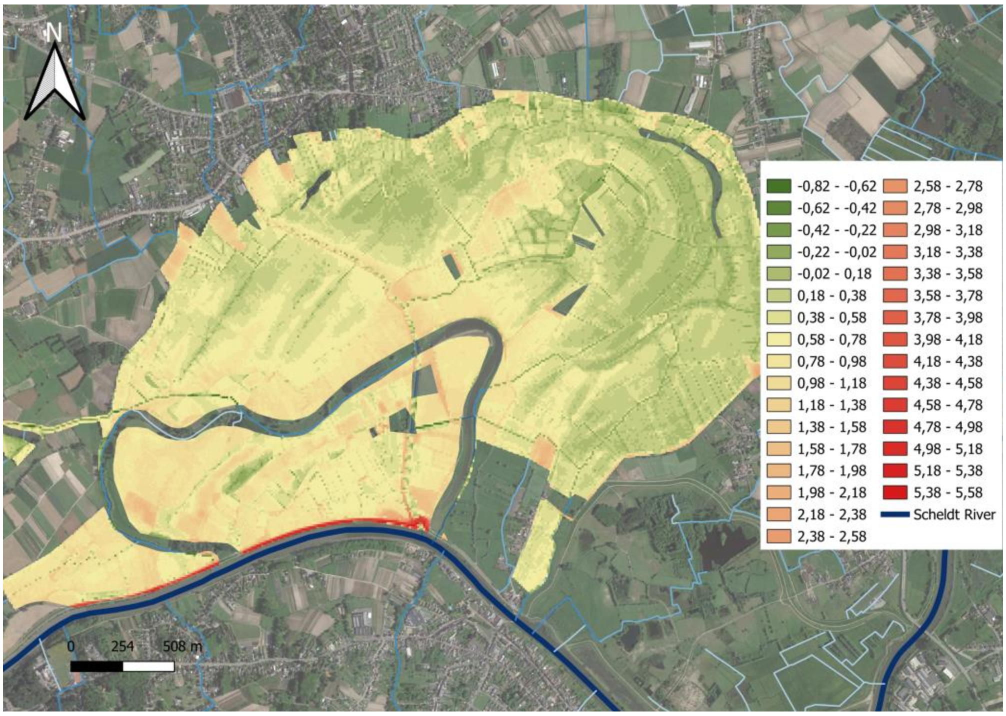

Figure 49 hf habitat

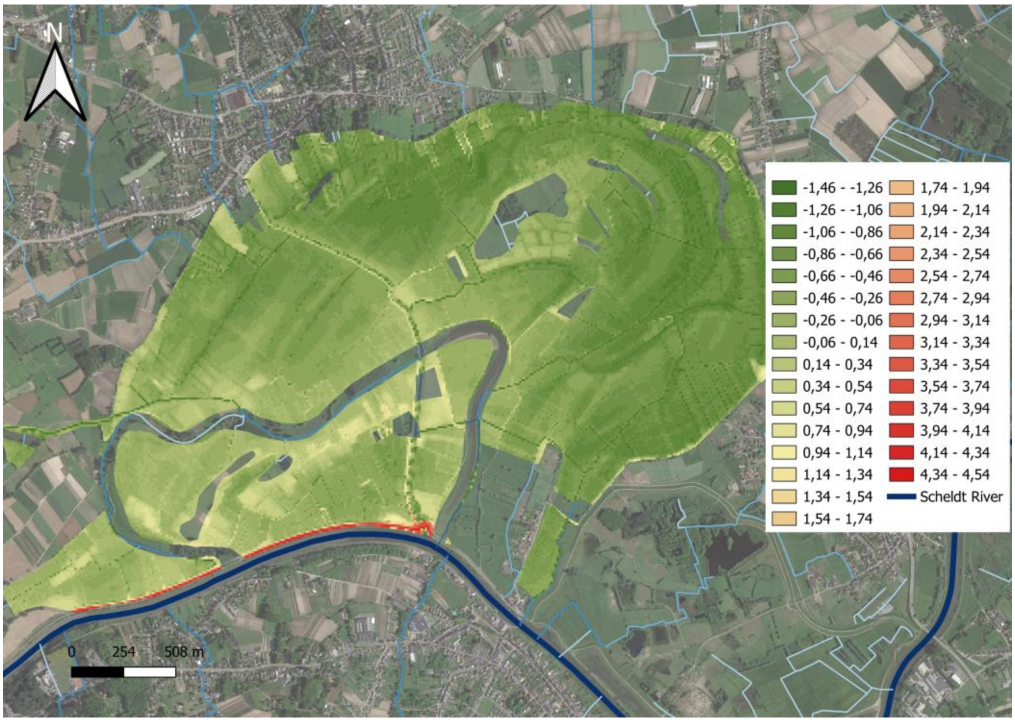

Figure 50 hpr habitat*

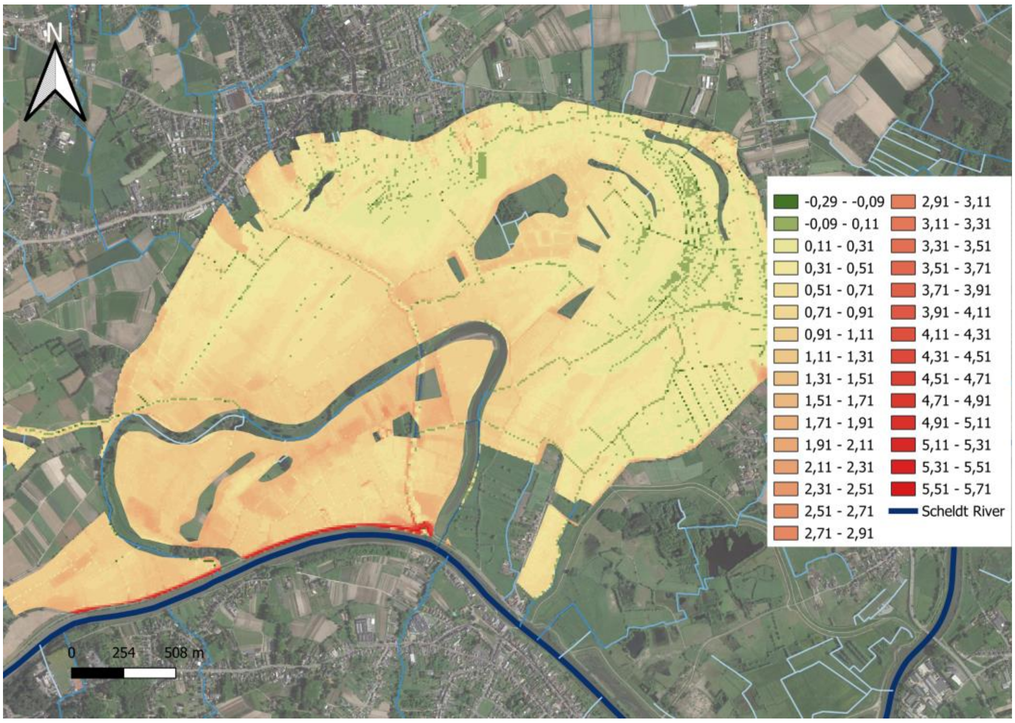

Figure 51 mc habitat

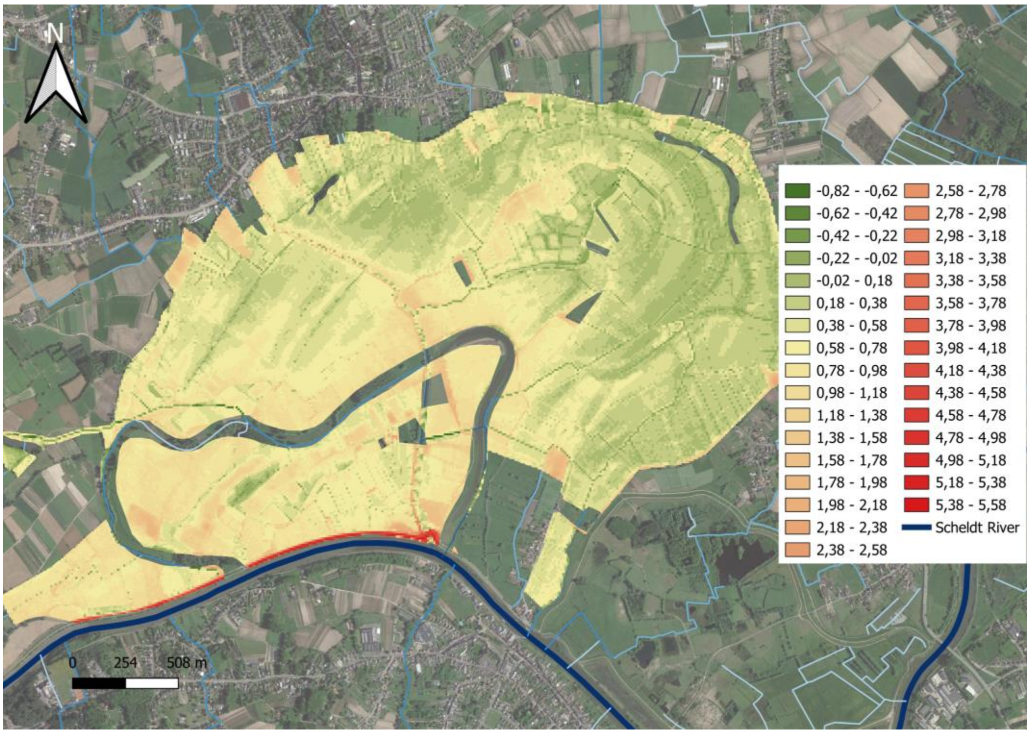

Figure 52 hc habitat

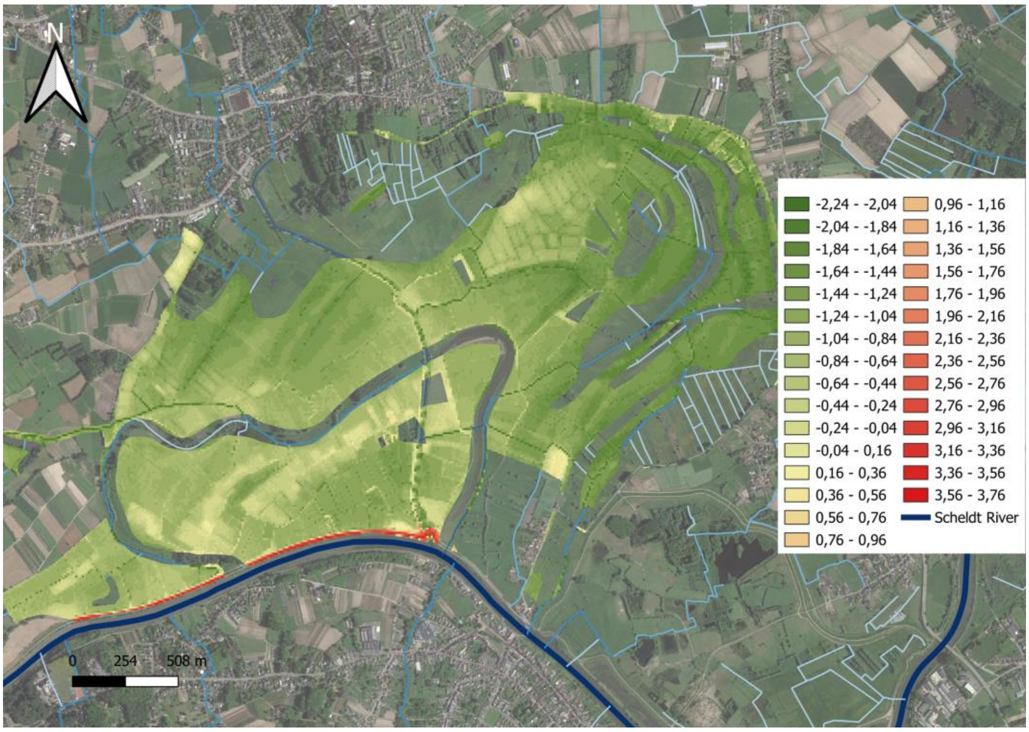

Figure 53 hu habitat

2) Future scenario with maximization (3.09 mTAW)

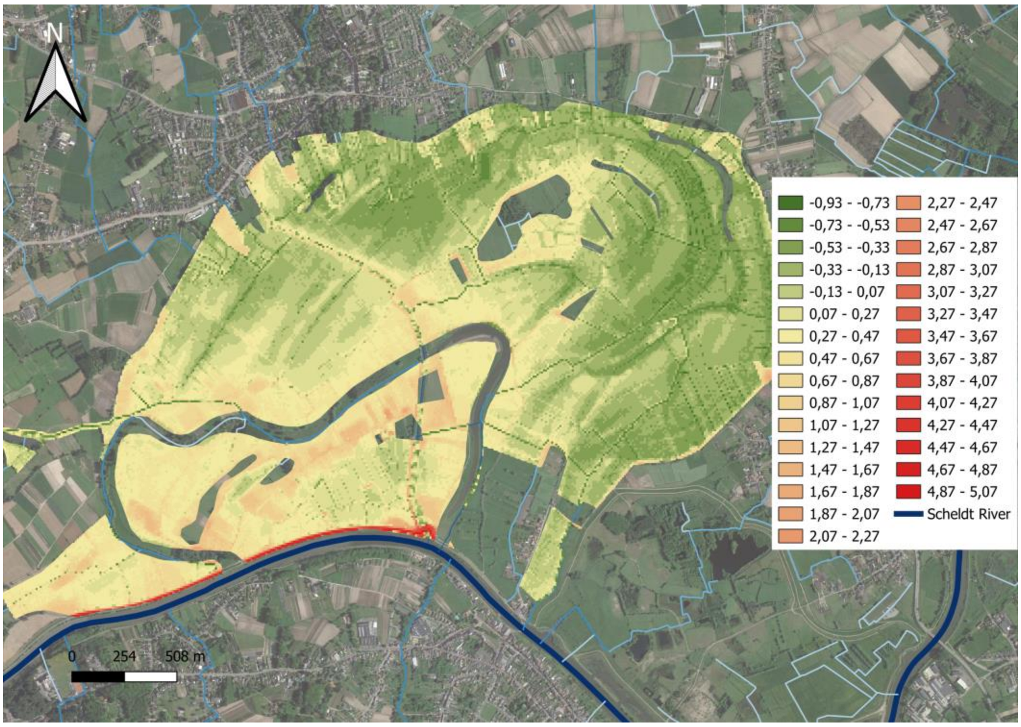

Figure 54 hf habitat

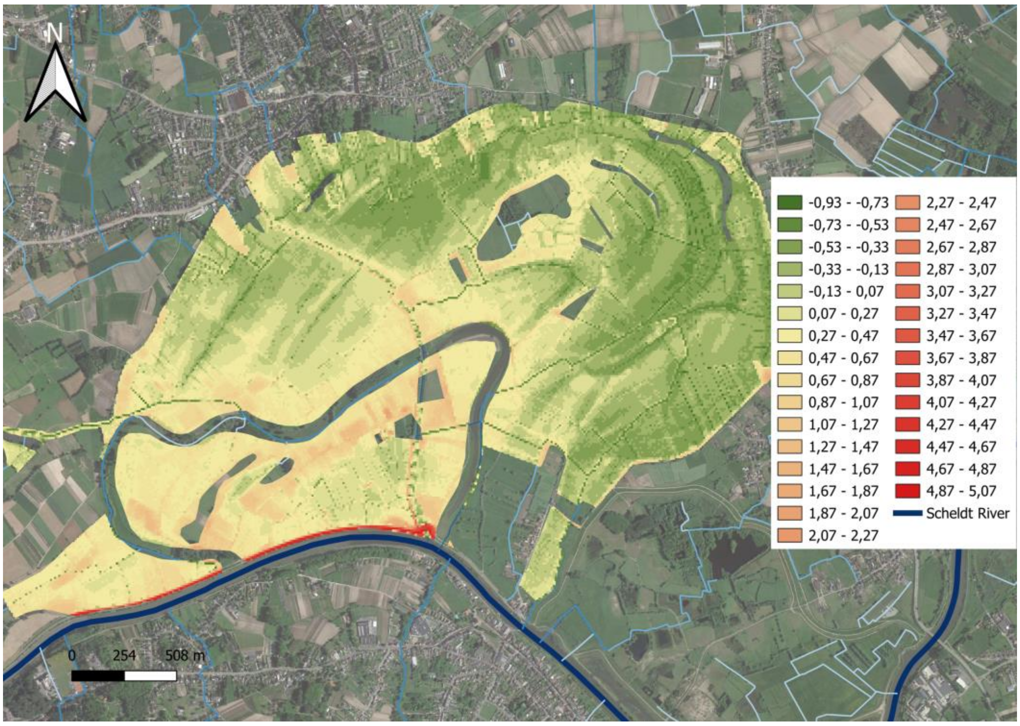

Figure 55 hpr habitat*

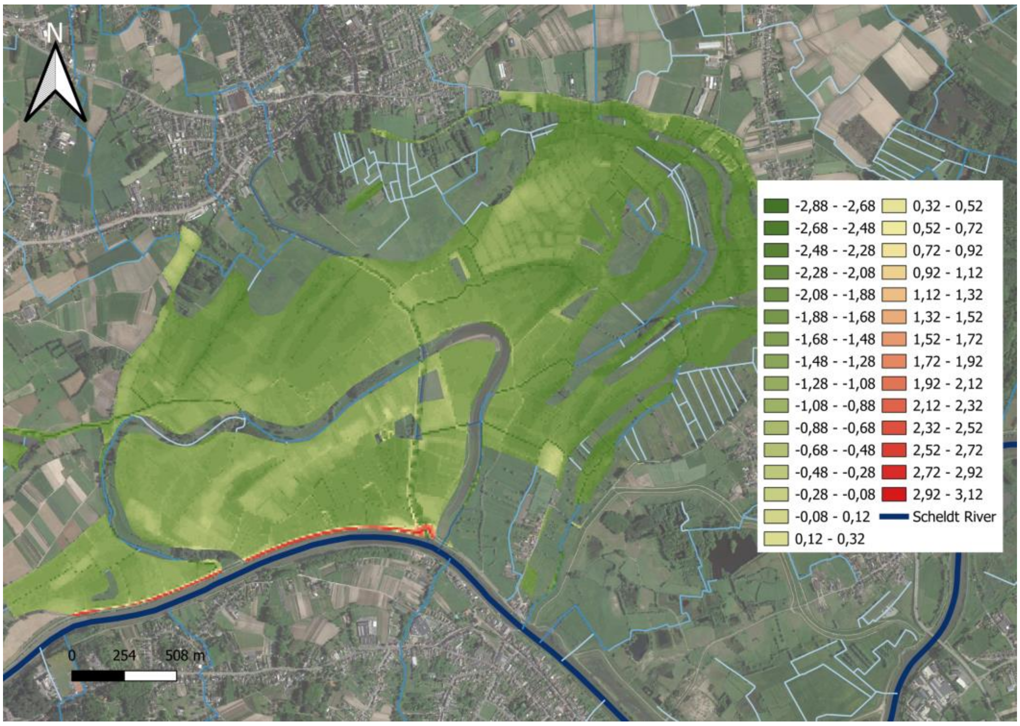

Figure 56 hu habitat

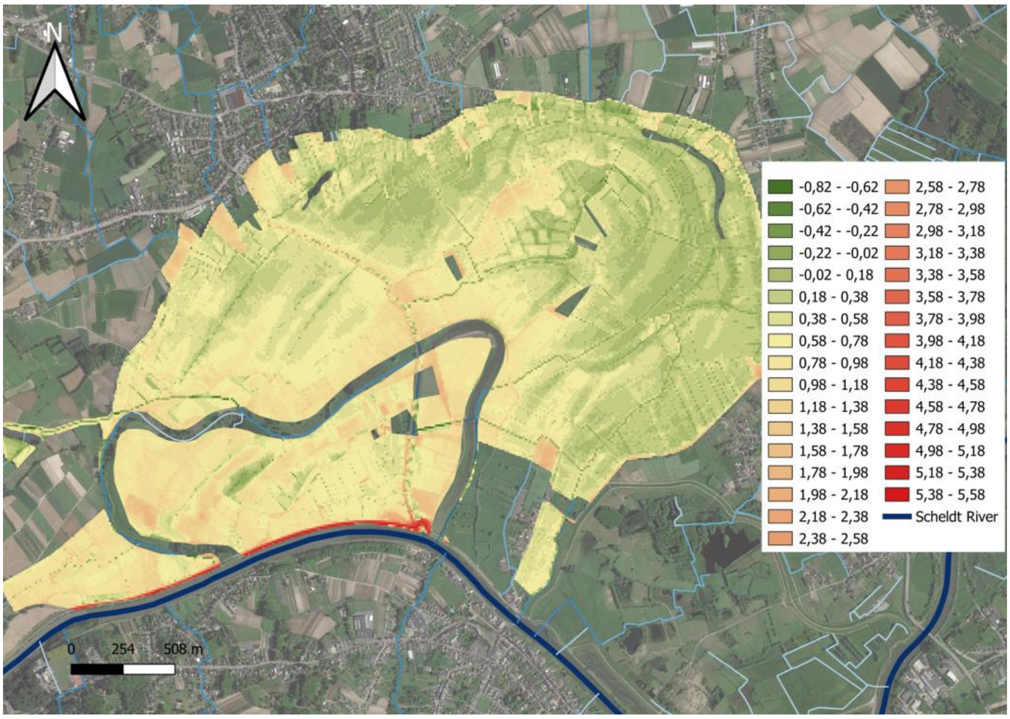

Figure 57 hc habitat

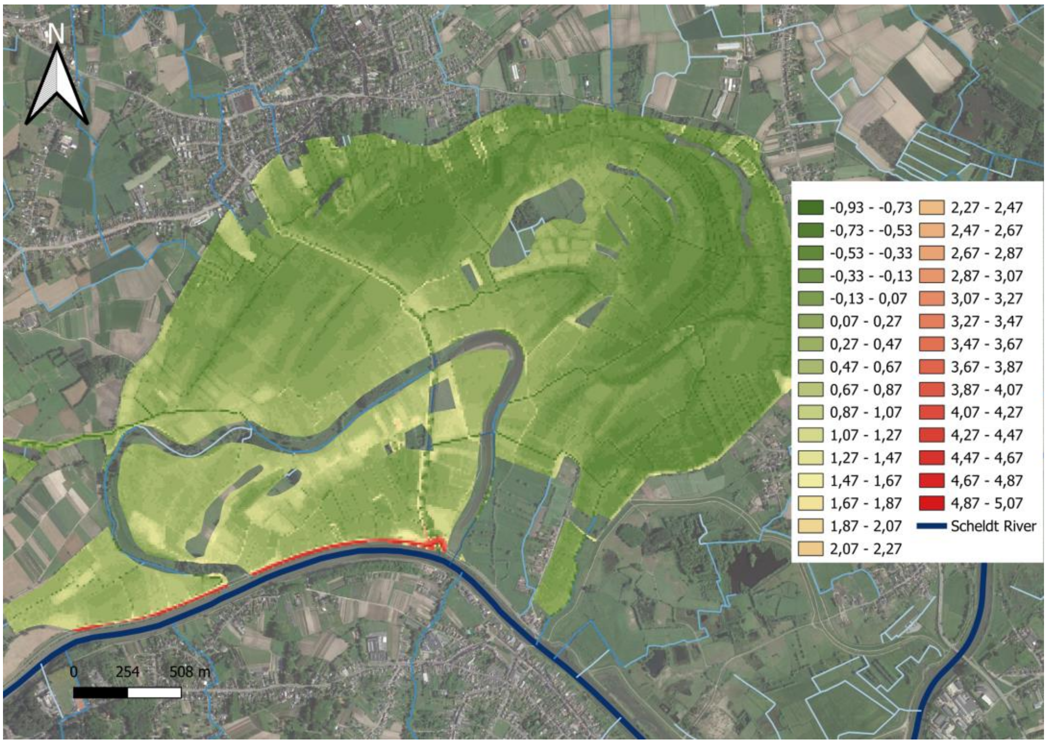

Figure 58 mc habitat