UTRECHT UNIVERSITY
MASTER'S THESIS WATER SCIENCE & MANAGEMENT

Impact of climate change on groundwater levels and flora of Natura 2000 area Punthuizen-Stroothuizen

Iris Koekkoek – 5948932

Supervisors
Niko Wanders – Utrecht University, n.wanders@uu.nl
Mirjam Hulsbos - TAUW, mirjam.hulsbos@TAUW.com
Christina Oosterhoff – TAUW, christina.oosterhoff@TAUW.com

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Summary

The summer of 2018 in the Netherlands was exceptional warm and sunny leading to a precipitation deficit that was three times higher than normal. Two out of four KNMI climate scenarios expect dryer summers in the Netherlands. A Natura 2000 area affected by the 2018 drought is Natura 2000 area Punthuizen-Stroothuizen. Desiccation, acidification and eutrophication impact the characteristic habitat types for Punthuizen-Stroothuizen. Recovery measures, assure future improvement of the groundwater level but climate change was not taken into account when assessing he potential effects of the measures.

Research goal and methods

The research objective is to gain insight into the impact of increasing summer precipitation deficits, predicted by KNMI'14 climate scenario W_h, on groundwater levels and achievability of vegetation objectives and to assess whether the taken measures are effective to keep the groundwater levels sufficiently high under a changing climate.

A hydrological model is used for this research. Six scenarios are ran: baseline conditions ($+W_h$-scenario), short-term measures ($+W_h$-scenario) and long-term measures ($+W_h$-scenario). Climate change is incorporated by precipitation and evaporation data. Maps are used to visualize the impact of measures and climate change on groundwater levels. Point data is extracted from the model to study the impact of climate change and measures on fluxes. Point data is also used to research the impact of climate change on flora by calculating *doelgaten*, fluxes and period of inundation at the location of monitoring wells. WaterVision is used to zoom out and give information about the impact of climate change on vegetation types over the whole area.

Results

Both short- and long-term measures result in higher groundwater levels in both winter and summer. Effects are larger in winter and groundwater levels increase more due to the long-term measures than short-term measures. Climate change has only small effects (-5 to +5 cm) in winter throughout the area. Groundwater levels decrease with 5 to 20 cm in summer. The short-term measures are not sufficient in summer to cope with climate change effects. The long-term measures are more effective and lead to increasing summer and winter groundwater levels in Punthuizen. For Stroothuizen, more measures are needed to cope with climate change. Both climate change and measures bring increasing fluxes in winter and spring, which is beneficial.

The current situation in Punthuizen-Stroothuizen is suboptimal for the desired diversity in flora, since groundwater levels are too low, periods of inundation too short and fluxes too low. Climate change results in lower GLGs and GVGs, shorter periods of inundation but somewhat higher fluxes. Climate change does put the achievability of the vegetation objectives more at risk. The proposed measures bring relieve, since they increase groundwater levels, fluxes and inundation times but more is needed.

Discussion

The functioning of the hydrological system is properly simulated by the model and therefore, the model can be used to draw theoretical conclusions on the effects of measures and climate change, regardless of the existence of residuals when forecasting groundwater levels. Uncertainty is present in the climate scenario due to interpolation factors and new insights into climate change. Also, only the effect of hydrological factors is taken into account when studying the impact of climate change on flora.

Conclusion

Measures and climate change (partly) neutralize each other. Conditions nowadays are suboptimal and more measures are needed to increase groundwater levels (especially in Stroothuizen) and obtain desired conditions for the flora.

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List of Abbreviations

BOT	Bottom of aquifer
GHG	Average highest groundwater level
GLG	Average lowest groundwater level
GVG	Average spring groundwater level
GXG	GHG, GLG and GVG together
KDW	Transmissivity
KNMI	Royal Dutch Meteorological Institute
PAS	Program to address and to manage nitrogen
PH	Punthuizen
SHD	Starting head
SH	Stroothuizen
STO	Storage coefficients
TOP	Top of aquifer
VCW	Vertical resistance

1. Introduction

The summer of 2018 in the Netherlands was exceptional warm and sunny. The period between the 15th of July until the 7th of August would have been the longest heatwave in history, but the 28th of July was cooler than 25 degrees Celsius, resulting in two separate heatwaves (KNMI, 2019e). Next to that, the average summer temperature was the highest ever seen. A high pressure area above Scandinavia increased evaporation in May and July and a shortage of precipitation lead to drought in Western Europa. For the Netherlands, the precipitation deficit was three times higher than normal with values of more than 300 mm (Arcadis, 2018). Only the drought of 1976 in the Netherlands was of similar extend with a precipitation deficit of 363 mm.

The Royal Dutch Meteorological Institute (KNMI) translated the research results of the IPCC rapport of 2013 to climate scenarios for the Netherlands. Two out of four scenarios expect that summers in the Netherlands will become dryer in the future (KNMI, 2019d).

The impacts of droughts can be even more extensive and can disturb agriculture, ecosystems, human health and the national economy. The damage due to the drought event of 2018 is estimated on 450 to 2,080 million euros (van Hussen, van de Velde, Läkamp, & van der Kooij, 2019). The drought of the summer of 2018 impacted protected areas in the Netherlands due to decreasing groundwater levels, for example Natura 2000 areas.

One of these vulnerable areas is Punthuizen-Stroothuizen, which is part of the Natura 2000 area Dinkelland near the border to Germany in Twente (Figure 1). Punthuizen-Stroothuizen lays on the transition area of higher sandy areas near the German border to the lower laying Dinkeldal to the west. The area of Stroothuizen is approximately 60 ha large and is a remainder of the former extensive moorland area in Eastern-Twente. The area of Punthuizen (Beuninger Achterveld included) is 135 ha large. Both areas consist of dry and wet moorland and a number of wet, low lying areas with fens and grasslands (Provincie Overijssel, 2019).

Desiccation, acidification and eutrophication impact the characteristic habitat types for Punthuizen-Stroothuizen due to inflow of nutrient enriched infiltrated rainwater and low groundwater levels (Staatsbosbeheer, 2017). Recovery measures, approved in 2017, assure future improvement of the groundwater level. These measures mainly focus on changes in (ground)water management by for example removing drainage in agricultural fields and fill up or decrease the depth of drainage ditches. Using these measures, more bulging of groundwater is expected, which decreases drought in vulnerable nature areas. However, these measures are not yet implemented and climate change is not taken into account when looking at the potential effects of the measures.

In Capel, et al., (2011) the authors mapped the changes in average spring (GVG) and average lowest (GLG) groundwater levels for the eastern parts of the Netherlands under a changing climate. The maps show that both spring and lowest groundwaterlevels will drop for the most extreme KNMI climate scenario in 2050 in the area surrounding Punthuizen-Stroothuizen. However, those maps show the whole eastern part of the Netherlands, so there is a lack of details on Punthuizen-Stroothuizen.

Based on this information, it is clear that drought will have a negative effect on the hydrological system and the nature of Punthuizen-Stroothuizen, but detailed effects are not yet identified. On top of that, it is uncertain whether the proposed measures to increase groundwater levels will be enough to sustain the vulnerable nature in the area considering the effects of climate change.

So, in this report we study the impact of future droughts on the resilience of the hydrological system of Punthuizen-Stroothuizen. Therefore, the research objective is to gain insight into the impact of drought on the hydrological system and the chances of survival for vulnerable flora in the Punthuizen-Stroothuizen in a changing climate and to assess whether the taken measures are effective to keep the groundwater levels sufficiently high.

The research question is: *What will be the impact of increasing summer precipitation deficits on groundwater levels in Natura 2000 area Punthuizen-Stroothuizen and what are the consequences of this change in groundwater level on the achievability of the vegetation objectives in the area?*

This study covers six sub questions in regarding hydrological change and the vegetation response to the measures and climate scenario W_h.

1. What are the groundwater levels in Punthuizen-Stroothuizen, excluding the proposed measures of 2017 and climate change?
2. What effects do the proposed measures of 2017 have on groundwater levels in Punthuizen-Stroothuizen?
3. What effects do the proposed measures of 2017 in combination with changing evaporation- and precipitation patterns, predicted by KNMI'14 climate scenario $W_{h,}$ have on the groundwater levels and fluxes in Punthuizen-Stroothuizen?
4. What is the current situation with respect to optimal conditions for the chosen vegetation types in Punthuizen-Stroothuizen according to point data and WaterVision-maps?
5. What is the effect of the proposed measures of 2017 on the achievability of optimal hydrological conditions for the chosen vegetation types in Punthuizen-Stroothuizen?
6. To what extent do increasing summer precipitation deficits, predicted by KNMI'14 climate scenario W_h, change the achievability of vegetation objectives, taken into account the proposed measures of 2017?

This research consists six parts. First of all, the area of Punthuizen-Stroothuizen is described with respect to lithology, hydrology and vegetation (Chapter 2). Afterwards, the necessary theory on which this research is built is presented. This theory section is divided into two parts. First of all, theory behind drought itself, it's impacts and the effect of climate change on droughts is described (Chapter 3.1). The second part focused on the theory behind the model that is used for this research (Chapter 3.2). Afterwards, the different steps taken and the data that is used during this research is stated in the methods and materials-section (Chapter 4). The results will be presented in the same order as the method and the sub questions (Chapter 5). Finally, the results will be discussed (Chapter 6) and this research ends with a conclusion (Chapter 7).

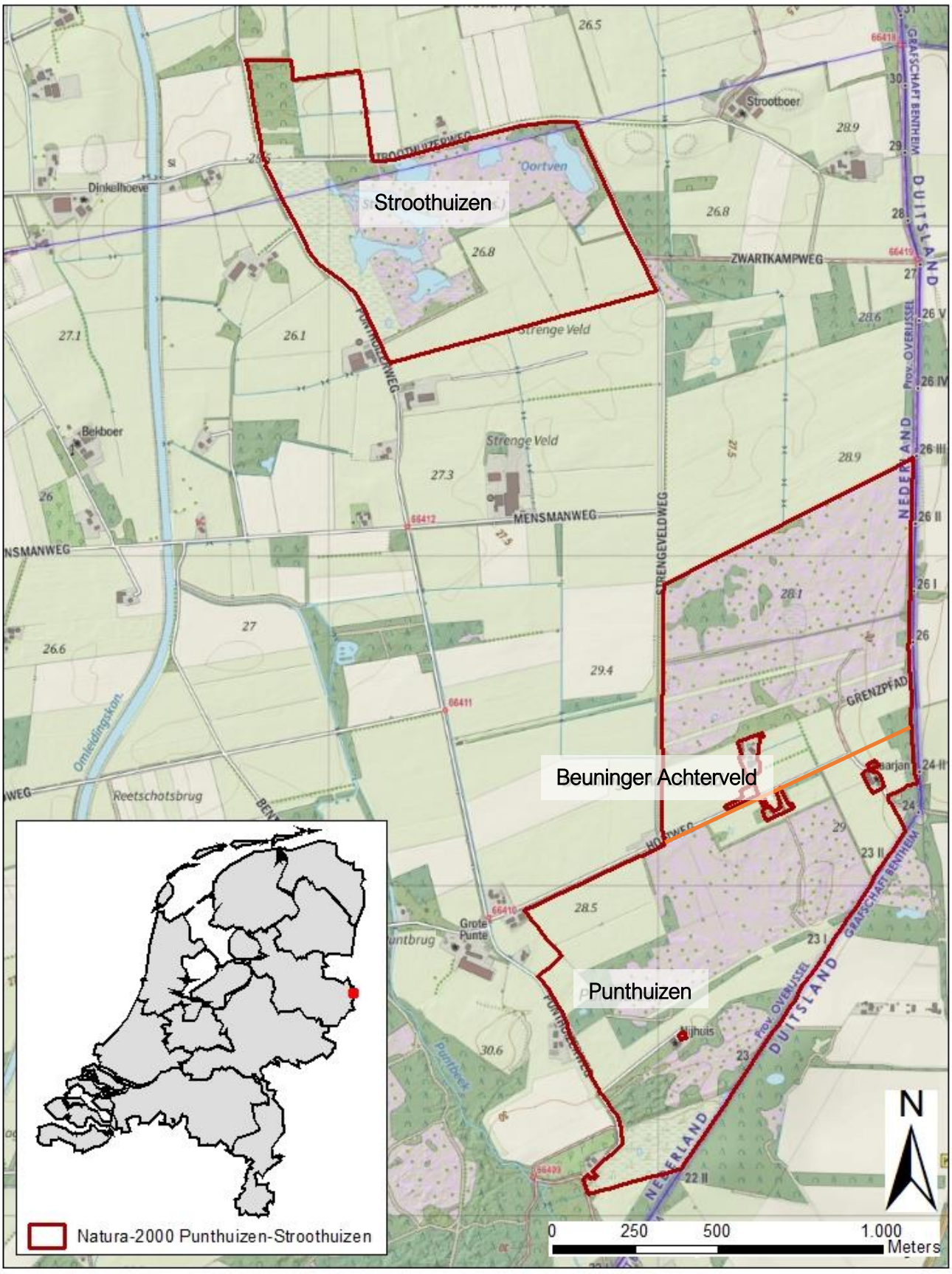

Figure 1: Location of the subareas Punthuizen and Stroothuizen, which are a part of Natura 2000 area Dinkelland

2. Site description

The areas included in this research are Punthuizen and Stroothuizen, which are part of Natura 2000 area Dinkelland. Natura 2000 area Dinkelland consists of four subareas: the stream valley of the Dinkel and three moorland areas: Punthuizen, Stroothuizen, and Beuninger Achterveld. Figure 1 shows the location of Stroothuizen, Beuninger Achterveld, and Punthuizen. The three areas lie between the stream valley of the Rammelbeek in Germany and the Puntbeek in the west and are surrounded by agricultural activities (mainly grassland).

The elevation in the area differs between 26 meters above sea level northern of Stroothuizen to approximately 29.5 meters above sea level south of Punthuizen. Abandoned river branches formed the small-scale topography in the area, resulting in a undulating relief. These river branches and higher eolian sand ridges are clearly visible when studying ground levels of Punthuizen (Figure 2). The topographic differences are important for the hydrological functioning (paragraph 2.1).

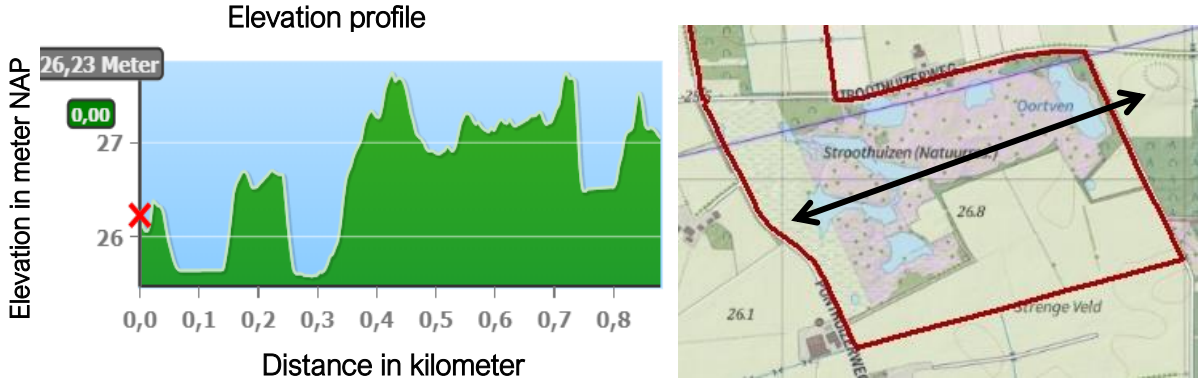

Figure 2: Cross-section of ground levels in Punthuizen

The average monthly temperature ranges from 1.97°C in January to 17.17°C in July (KNMI, 2019a). Average yearly precipitation from 1974 to 2018 is 760 mm (KNMI, 2019b). The annual average for the Netherlands is approximately 800 mm per year. The KNMI (2019b) shows large fluctuations in monthly precipitation in Twente. For example, precipitation in January 2015 was approximately 110 mm, while in 2006 this was only 20 mm. The same behavior is observed in the summer months, like July.

2.1 Lithological and hydrological system of Punthuizen-Stroothuizen

The following part is based on Dongen, Eysink, Ent, & Brummelman (2017). The geohydrological composition of Punthuizen-Stroothuizen is quite simple (Figure 3). It consists of a permeable sand layer (yellow and orange) on a low-permeable basis of sandstone in the southern part (grey) and clay in the northern part (red). The thickness of the permeable sand layer varies from 25 to 40 meter and increases from southeast to northwest. The geological composition is more complex near Stroothuizen, due to clay layers with different depths (darker yellow parts on the left in Figure 3), two permeable zones are distinguished. West of Stroothuizen, the thickness of the permeable layer decreases abruptly from 40 to 20 meters leading to groundwater seepage through the land surface. For the whole area, regional groundwater flows from southeast to northwest. In addition to (sub-)regional groundwater flow, local groundwater patterns, like bulging and flow of relatively young groundwater from the higher eolian sands ridges to lower parts of the area, are important.

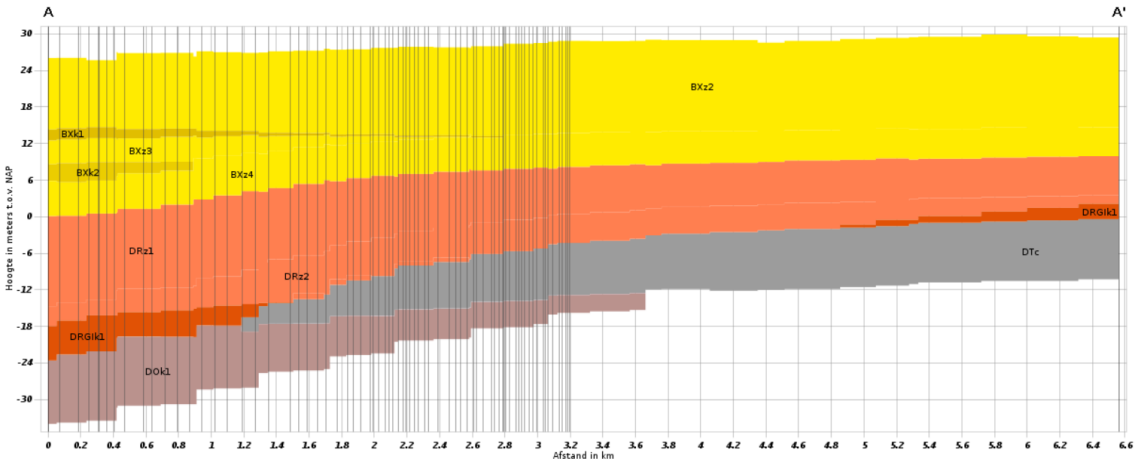

Figure 3: REGIS II v2.2 Lithological cross-section Punthuizen-Stroothuizen

Groundwater flows and groundwater levels in the agricultural areas, Punthuizen, Stroothuizen and Beuninger-Achterveld are influenced by drainage ditches, the Rammelbeek, the Puntbeek and the diversion canal of the Dinkel. Larger systems like the Puntbeek, Rammelbeek and the diversion canal affect mainly the drainage basis, resulting in groundwater levels that drop rapid and deep in summer period. The Puntbeek is the drainage basis for Punthuizen. Local drainage systems affect mainly winter- and spring groundwater level and often run dry in summer and do not affect groundwater levels during the summer season. Exceptions are deep drainage ditches in Germany. These drainage ditches together form the upper reaches of the Rammelbeek. So local waterways affect mainly winter and spring water levels and larger channels affect summer levels by drainage.

Figure 4: REGIS II v2.2 Cross-section projected on map

Topography is important in the Punthuizen area. Based on the location, on the slope between the eolian sand ridges and low laying areas, seepage and infiltration processes occur. Low laying areas inundate in winter and the eolian sand ridges form the infiltration area since unsaturated zones exist only in higher regions in winter, resulting in bulging. The hydrological gradient, which is following the surface level, is the driver for local groundwater flow.

Topography is also the main influencer for seepage. Moving downward from the sand ridges, the gradient decreases due to a decrease in slope, resulting in a smaller flux in the lower areas than in the higher areas. The difference in flux results in seepage (upward flux) to the surface. Where seepage enters the surface depends on the groundwater level and inundation level of the low-laying area. Base enriched seepage mainly occurs at the edges of inundated low-laying areas in Punthuizen. Due to bulging in the eolian sand ridges in winter, pressure increases on deep base enriched groundwater. This pressure causes seepage just above inundation level. This base enrichment is due to local hydrological processes or due to the interaction between these local processes and underlying base enriched groundwater from a larger groundwater system.

In Stroothuizen, similar processes occur. Topography causes seepage on the slopes of eolian sand ridges due to the gradient in elevation. This occurs in low-laying areas which are not or shortly inundated and are also fed by deep base enriched groundwater.

However, bulging of groundwater happens insufficiently in these local systems to secure influx of groundwater to fens. Another difference between Punthuizen and Stroothuizen is the base enriched seepage in spring in the western part of Stroothuizen from deep groundwater.

2.2 Vegetation in Punthuizen-Stroothuizen

The following part is based on Dongen, et al. (2017). Base enriched groundwater is an important influencer of vegetation in Punthuizen-Stroothuizen. Punthuizen-Stroothuizen consists of different habitat types or gradient types due to different (a)biotic circumstances. The vegetation gradient depends on inundation of the low-lying areas with rainwater and base enriched groundwater. Due to the differences in topography and yearly inundation levels, specific vegetation types are found in horizontal strips following these levels, based on their groundwater level and base enrichment preferences. Moisture, acidity and amount of nutrients, which are influenced by groundwater level, inundation and groundwater bulging, also influence where vegetation types are found.

For this research, we use habitat types that are sensitive to changes in groundwater level (desiccation), amount of nutrients (eutrophication) and acidity: *Zwak gebufferde vennen*[1], *vochtige heide*[2], *droge heide*[3], *blauwgraslanden*[4] and *pioniervegetaties met snavelbiezen*[5] (Staatsbosbeheer, 2017). These different habitat types are a result of the differences in wet and dry circumstances and lack or enrichment of base and follow the elevation gradient. We find *droge heide* on the higher, dryer parts with a thicker unsaturated zone. A little downhill, we find *vochtige heide and blauwgrasland* due to the influence of acidic rainwater and young, base-lacking groundwater. Just above the low laying area, a strip does not inundate but seepage is strongest here in winter. In this strip we find the Parnassia (*Blauwgrasland).* Also in the areas with frequent inundation in winter, we find *pioniersvegetaties met snavelbiezen*. We find *zwakgebufferde vennen* in the lowest areas with high inundation frequencies.

Sensitivity to changes in physical factors (desiccation and wetting) and chemical factors (acidification and eutrophication) differs per habitat type (Table 1).

Table 1: Sensitivity of habitat types to changes in physical and chemical factors (Ministerie van Landbouw, 2019a). The color indicates sensitivity: very sensitive ■■■, sensitive ■■, not sensitive ■ .

Habitat type	Desiccation	Wetting	Acidification	Eutrophication
Zwakgebufferde vennen	■■■	■	■■■	■■■
Vochtige heide	■■■	■	■■■	■■■
Droge heide	■	■■■	■■■	■■■
Blauwgraslanden	■■	■■	■■	■■■
Pioniersvegetaties met snavelbiezen	■■■	■	■■	■■

[1] Clear-water lakes or lochs with aquatic vegetation and poor to moderate nutrient levels (Oligotrophic to mesotrophic standing waters with vegetation of the *Littorelletea uniflorae* and/or of the *Isoëto-Nanojuncetea*) (UKTAG, 2003)
[2] Wet heathland with cross-leaved heath (Northern Atlantic wet heats with *Erica tetralix*) (UKTAG, 2003)
[3] European dry heaths (UKTAG, 2003)
[4] Purple moor-grass meadows (*Molinia* meadows on calcareous, peaty or clayey silt-laden soils (*Molonion caeruleae*)) (UKTAG, 2003)
[5] Depressions on peat substrates (Depressions on peat substrates of the *Rhynchosporion*) (UKTAG, 2003)

Information on optimal moisture conditions for the habitat types is important, since it shows the range in which groundwater can vary and still is optimal for the habitat types (Table 2). When moisture conditions exceed these conditions, they become sub-optimal.

Table 2: Optimal moisture conditions per habitat type, ■ optimal, ■ near optimal (Ministerie van Landbouw, 2019a; Provincie Overijssel, 2017)

	Deep water	Shallow permanent water	Shallow, drying water	Inundating in winter	Very wet	Wet	Very moist	Moist	Moderately dry	Dry
Zwakgebufferede vennen[6]	■	■	■	■						
Vochtige heide[7]					■	■	■			
Droge heide[8]								■	■	■
Blauwgraslanden[9]					■	■				
Pioniersvegetaties met snavelbiezen[10]				■	■	■	■			

The vegetation gradients in Punthuizen-Stroothuizen have relationships with relief and water systems. However, dynamics are not easily understood since the groundwater level, time span of inundation and base enrichment and weather all affect the system. For example: when groundwater level gets too low in summer, base enriched seepage decreases in winter, which results in acidification. Also, bulging in eolian sand ridges steers local groundwater flow from sand ridges to low-laying areas in winter. In inundation areas, base enriched groundwater and rainwater mixes, resulting in weakly buffered conditions. If and how long areas inundate depends on weather conditions.

Habitat quality thus depends on interactions and conditions and results in different vegetation gradients in Stroothuizen and Punthuizen.

[6] Zwakgebufferde vennen: GVG: < -50 to -5 cm below surface
[7] Vochtige heide: GVG: -20 to > 40 cm below surface
[8] Droge heide: GVG: >40 cm below surface
[9] Blauwgraslanden: GVG: -5 to 25 cm below surface
[10] Pioniersvegetaties met snavelbiezen: GVG -20 to 25 cm below surface

3. Theory

The focus of this research is on the impact of dryer summers on the hydrological system and flora of Punthuizen-Stroothuizen. The first part of this theory section focusses on the theory behind drought, its impacts and the effect of climate change on droughts. Figure 5 shows how the different theory parts are brought together and what questions are answered.

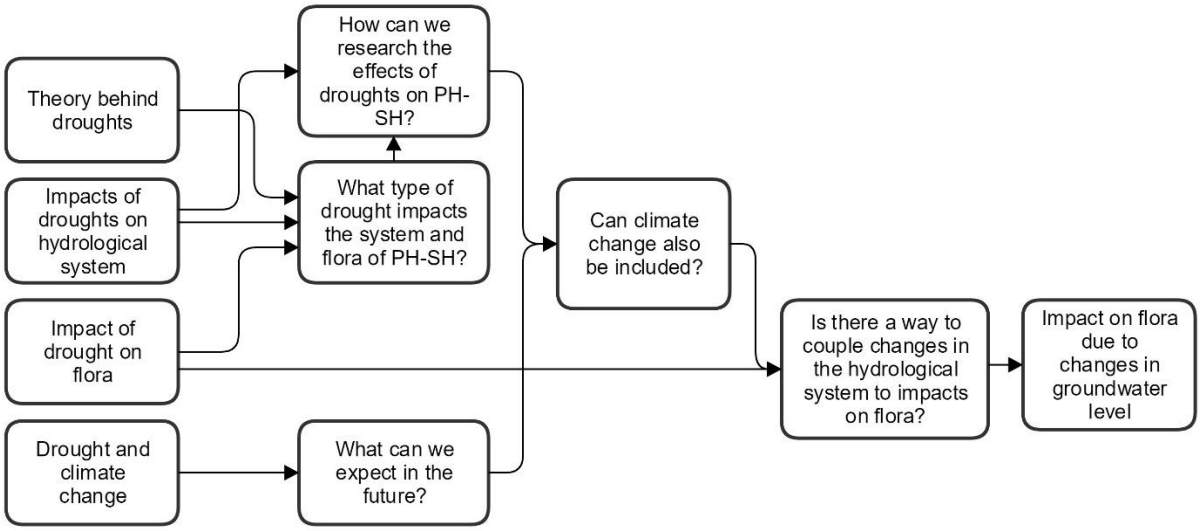

Figure 5: Connections and questions to be answered in the theory section

The second part of this theory section focusses on the hydrological model that is used for this research and describes what is included into the model, and how climate change can be incorporated.

3.1 Droughts, its impacts and climate change

3.1.1 Theory behind droughts

Wilhite & Glantz (1985) state that droughts happen in areas with high and low amounts of precipitation and describe drought as a deviation from "some long-term average condition of balance between rainfall and evapotranspiration in a particular area". Drought is thus described as an unusual period where the balance between rainfall and evapotranspiration is different than normal in a specific area. Different types of droughts are distinguished:

Meteorological droughts happen when "dry weather patterns dominate an area" (NOAA, 2019) and thus precipitation deficiencies are present in that specific area. It can be for example measured by the amount of days where precipitation is less than normal or a specified threshold. This leads to reduced infiltration, runoff and groundwater recharge (University of Nebraska-Lincoln, 2019). However, some areas of the world experience a dry season, where this definition is more difficult to use.

Meteorological droughts can result in *agricultural droughts* since it can lead to deficiencies in soil moisture, reduced groundwater levels and mismatches between actual and potential evapotranspiration. This all may lead to plant water stress and reduced biomass and yield (University of Nebraska-Lincoln, 2019).

Hydrological droughts refers to shortages of water in the hydrological system by reduced precipitation (Loon, 2015). Hydrological droughts become evident when water levels in streams and (groundwater)reservoirs drop and water availability therefore decreases.

"*Socioeconomic drought* occurs when the demand for an economic good exceeds supply as a result of a weather-related shortfall in water supply" (University of Nebraska-Lincoln, 2019). This can be for example reduced hydropower supply.

Finally, Novák (2009) describes *physiological droughts* as "deficiency of water, not covering plant needs". Water can be present during a physiological drought, but it is for example frozen or of bad quality by high soil salinity so plants cannot absorb it.

Local area characteristics influence the risk of drought by for example soil type, ground level, (lowest and highest) groundwater levels and whether groundwater regulation is in place. Drought damage can be impacted by seepage and (natural) subsidence (Wilschut, 2018) and areas may be more vulnerable to drought due to for example vegetation species and wooden foundation.

3.1.2 Impacts of drought on hydrological system

Lack of precipitation is the primary cause of drought. Groundwater normally reacts slow to drought situations when surface water is not groundwater fed (Tallaksen & Van Lanen, 2004). Groundwater is a resilient resource and can act as a moderator when it comes to precipitation deficits (British Geological Survey, 2019). The period of time between a meteorological drought and a groundwater drought can be months or even years. A decline of flow in streams and rivers, dropping water levels in lakes and reservoirs and increasing water depths in wells are effects of droughts on the hydrological system that people can see.

According to Tallaksen & van Lanen (2004), drought sensitivity differs per catchment and depends on catchment characteristics and hydrological processes of the area. A drop in the groundwater table is the first sign of a groundwater drought. However, "groundwater storage properties strongly control how fast water levels fall" (Tallaksen & Van Lanen, 2004). When the reaction to periods of low precipitation is slow, systems are mostly large. Also, topography, land-use, soil type, hydrogeological conditions, lakes and stream networks are important properties in groundwater systems. All these properties influence the response to droughts and a thorough understanding of the system of Punthuizen-Stroothuizen is necessary to estimate its reaction to drought.

The hydrological system of Punthuizen-Stroothuizen is strongly driven by weather patterns. Both dry winters and dry summers affect the area. Groundwater levels in winter influence the groundwater level in summer and the other way around. Stream networks, topography and soil type are the main properties of influence in Punthuizen-Stroothuizen. Groundwater levels decrease at high rate in summer. This is mainly due to permeable sandy soil types and the stream networks of the Puntbeek, Rammelbeek and the diversion canal, which form the low-laying drainage basis. In winter, local drainage systems are more important. In summer, groundwater levels drop to regional drainage basis and local groundwater fluxes stop.

The hydrological system of Punthuizen-Stroothuizen is already modelled by TAUW for PAS (Program to Address and to Manage Nitrogen) in iMOD and MetaSWAP. Also the measures that will be taken in Punthuizen-Stroothuizen are included in this model and the effect of those measures on groundwater levels is already known. Since this model incorporates the hydrological system and meteorological inputs, it can be used to model the impacts of droughts. Paragraph 3.2 and Appendix 1 give more information on the model.

3.1.3 Impact of drought on flora

Water is important to plants since 80 to 90% of the biomass of non-woody plants is water. Also, water is the major medium for "transporting metabolites and nutrients through plants" (Lisar, Motafakkerazad, Hossain, & Rahman, 2012). Due to drought, the plant water potential and turgor decreases, resulting in difficulties executing normal functions (Lisar et al., 2012). Drought results in lower groundwater levels (paragraph 3.1.2). Two causes of water stress in plants are

distinguished: when water supply to their roots becomes limited and when transpiration becomes increasingly large (Lisar et al., 2012).

According to Wilschut (2018), two groundwater processes are important when analyzing nature damage. First of all, due to lower groundwater levels, capillary action decreases, resulting in decreased moisture content for transpiration and interrupted water supply to plants. This effect is relatively large at shallow GLGs and/or limited rootzone thickness. In areas with deep groundwater levels, a lowering of the average lowest groundwater level has no impact. In these areas, vegetation relies on pendular water. This water clings to particles in the unsaturated zone. This is the second important mechanism.

Most characteristic habitat types of Punthuizen-Stroothuizen have specific requirements with respect to groundwater conditions and levels (Table 1 and Table 2). (future) Groundwater conditions should fit the characteristic vegetation types. A tool to research whether groundwater conditions matches vegetation objectives, is WaterVision Nature[11]. WaterVision is used here to test existing vegetation objectives against (future) groundwater conditions.

3.1.4 Drought, climate change and climate scenarios

The Royal Dutch Meteorological Institute (KNMI) translated the IPCC report of 2013 to climate scenarios for the Netherlands. The scenarios "are designed to give a quantitative visualization of a range of climate conditions to which our country and its surroundings are presumably exposed to in the coming century" (KNMI, 2014). The different climate scenarios are computed by combining global mean climate forcings and regional factors like local feedbacks and circulation responses. However, the basis lies in the increase of global mean temperature.

In general, scenarios show "higher temperatures, accelerating sea level rise, wetter winters, more intense showers and drier summers" (KNMI, 2019c). The KNMI developed four scenarios for climate change until 2050 and 2085. Each scenario is based on a different storyline and differ in the amount of global warming (Moderate or Warm) and/or changes in air circulation patterns (Low or High). Also, they are divided into two "pools": one with a strong regional response and one with a relatively weak regional response. The strong regional response results in wetter winters and drier summers, while the weaker response results in smaller precipitation changes. "The response of other variables (temperature, wind speed, evaporation) are derived from these pools, ensuring a consistent set of variables grouped together in each scenario" (KNMI, 2014).

The amount and temporal distribution of both precipitation and evapotranspiration will be affected by global warming (Witte, et al., 2015). Droughts will set in quicker and will be more extreme and precipitation becomes more concentrated in time resulting in changes in water balances.

From 1910 to 2013, precipitation increased over all seasons, except summer, resulting in an increase of 25.9% (KNMI, 2014) and will continue to increase in all of the scenarios. However, two scenarios expect a drop in summer precipitation for 2050. With respect to winter precipitation, all scenarios expect an increase (KNMI, 2014). Also, the likelihood of extreme showers and hail increases. Changes in precipitation patterns have a direct effect on plants, since the groundwater level depends on infiltration of precipitation. Groundwater levels may thus be lower in summer due to a reduction in precipitation, but may be higher in winter.

On top of that, temperature will continue to rise and the amount of warm summer days and the likelihood of heatwaves increase (KNMI, 2015). Increased temperatures result in higher evaporation rates, both from soils and from plants (NCCO, 2019). According to the KNMI (2014) potential evaporation in the growing season increased with 11.9% between 1958 and 2013.

[11] Waterwijzer Natuur

Since this research focusses on the impact of reduced summer precipitation, the focus will be on scenario Wh. The W_h scenario includes high global temperature increases and large changes in air circulation.

3.2 Model description

The model made by TAUW is divided in two parts. The unsaturated zone is modelled by MetaSWAP and is used to simulate "the process of groundwater recharge and discharge through the unsaturated zone" and interactions between soil, vegetation and atmosphere (Vermeulen, et al., 2017). MetaSWAP requires a high number of input variables to simulate interactions in the unsaturated zone (Appendix 1.3). Meteorological data (precipitation and evaporation) is the only input that "should be available in the form of a step-function with a time interval of t_s" (Walsum, Veldhuizen, & Groenendijk, 2011). In the model of TAUW, only daily natural precipitation is included. For evaporation, Makkink reference crop evapotranspiration is used.

MODFLOW is used to model the saturated zone. Both models include the processes of groundwater recharge and capillary rise (Gurp, 2016). However, MODFLOW simulates both horizontal and vertical groundwater flow in the saturated zone and MetaSWAP only simulates the vertical direction but is divided into multiple parallel, vertical columns. MetaSWAP thus assumes "that unsaterated flow takes place within parallel, vertical columns, with each column connecting to a simulation unit of a groundwater model" (Walsum & Groenendijk, 2008).

Since the unsaturated zone in MetaSWAP is modelled in one dimension (vertical) and the saturated zone in MODFLOW in three dimensions, a coupling has to be made. An i-link (integral) is used, in which the groundwater level of the Soil-Vegetation-Atmosphere-unit in MetaSWAP and the head in MODFLOW are kept equal.

When MetaSWAP and MODFLOW are coupled, regional groundwater flow needs to be calculated by MODFLOW. MODFLOW uses Darcy's law to model "the flow of a homogeneous incompressible fluid through a porous medium" (Walsum, Veldhuizen, & Groenendijk, 2011). In MODFLOW, the aquifer is divided into a system with a grid of blocks or cells. Rows, columns and layers describe the location of a specific cell (Harbaugh, 2005). The continuity equation is used to calculate groundwater flow and assumes "the sum of all flows into and out of the cell must be equal to the rate of change in storage within the cell" (Harbaugh, 2005). The continuity equition is solved per cell and for each time step. The heads at the beginning of the time step are known and the head of the end of the time step has to be obtained by solving the equation.

A more elaborate description about the model and input data can be find in Appendix 1.

3.3 Model and climate scenarios

Precipitation data and Makkink reference evaporation are the only daily data that can be fed to the model to include climate change, since the model uses the Makkink method for calculating evapotranspiration. If the Penman-Monteith method was used, other variables like (mean, daily maximum and daily minimum) air temperature, relative sunshine duration, radiation intensity, humidity and wind speed could be fed to the model. Table 3 shows the baseline values and changes in precipitation and evaporation due to the climate scenario W_h.

Table 3: Climate change induced meteorological changes (KNMI, 2015)

Year	Indicator	Climate 1981-2010 (reference period)	Values for the climate around 2050 for Wh
Precipitation	Mean amount	851 mm	+5%
Evaporation	Potential evaporation (Makkink)	559 mm	+7%
Winter			
Precipitation	Mean amount	211 mm	+17%
	Year-to-year variation	± 96 mm	+17%
	Number of wet days (≥ 0.1mm)	55 days	+2.4%
	Number of days ≥ 10 mm	5.3 days	+35%
Spring			
Precipitation	Mean amount	173mm	+9%
Summer			
Precipitation	Mean amount	224	-13%
	Year-to-year variation	± 113 mm	-4 to +2.2%
	Number of wet days (≥ 0.1mm)	43	-10%
	Number of days ≥ 20 mm	1.7 days	-8.5 to +14%
Evaporation	Potential evaporation (Makkink)	266 mm	+11%
Autumn			
Precipitation	Mean amount	245 mm	+7.5

The Makkink evaporation and precipitation data is available as daily grid-file which can be fed to the model by the mete_grid input file. This file states which precipitation and evaporation files belong to which day. The grid datasets "contain interpolated daily maps of precipitation and Makkink evaporation" (Sluiter, 2014). Daily data is available as historical interpolated data for the period 1910-2015. With respect to the precipitation data grids, the original data contains cumulative precipitation over 24 hours starting at 08:00 measured at KNMI precipitation measurement points. Between all those points, interpolation is needed to cover the whole country. The used interpolation method is ordinary kriging, which is based on the spatial correlation, described by a variogram, and linear combination of the measured values (Soenario, 2009).
The evaporation grids contain Makkink reference evaporation data over 24 hours starting at 00:00. The Makkink evaporation is calculated using incoming radiation and temperature measured by the KNMI network. Also, the Makkink evaporation is interpolated, using the Thin Plate Spline method.

The KNMI composed historical interpolated data for the period 1910-2015 transformed to all the four climate scenarios. A transformation program "transforms meteorological time series by applying monthly 'change factors'" (Bakker, 2015). For precipitation two steps are taken: first, the wet-day frequency is adjusted and second, the distribution of wet-day amounts is changed.

The change in wet-day frequency is based on the "projected relative changes per month according to the KNMI'14 scenarios" (Bakker, 2015). So for each scenario, a change in the amount of wet days per month is available. When this change is negative, days have to be 'dried'. When the change is positive, days have to be 'wetted'. This drying or wetting of days is done using two steps. First of all: "for all twelve calendar months, a set of target precipitation amounts/days is defined that is indictive for the amounts that should be dried" (Bakker, 2015). The amount that should be dried is composed by combining days from different precipitation percentiles and is thus uniformly chosen over all percentiles. Afterwards, days are dried or wetted. Whether days

are dried is based on their amount of precipitation and whether the day before and after are already dry/wet. For wetting of dry days this is based on the number of preceding wet days. Afterwards, to change the distribution of wet-day amounts a power-law transformation is applied.

The Makkink reference evaporation is not directly calculated using the reference data, but is obtained by using the transformed daily temperature and global radiation (Bakker, 2015). Changes in all the different percentiles are provided by the scenarios. These changes are implemented by quantile scaling. For example, the "first percentile of the daily minima in winter and the 99th percentile of daily maxima in summer" is expected to increase. Also changes in other percentiles and regional change factors are provided.

The global radiation is changed due to more frequent eastern winds in summer. Linear transformation is used to obtain future time series of global radiation.

The changes of averages and variability, as projected by the chosen scenario, are projected on the given historical temperature and precipitation data (KNMI, 2015a).

3.4 Wrap-up

Hydrological, physiological and physical droughts are the types of drought that can affect the hydrological system and flora directly. Drought becomes apparent in hydrological systems by dropping (ground)water levels, which is also the case in Punthuizen-Stroothuizen during summer. This is thus the direct reflection of a hydrological drought. Flora is impacted by decreasing groundwater levels during hydrological droughts.

The available groundwater model reflects the local situation of Punthuizen-Stroothuizen and is made to reflect changes in groundwater level. On top of that, meteorological inputs are embedded in this model. Based on this, we can say that the model can reflect changes in groundwater level based on changes in meteorological input. These meteorological inputs are extracted from climate change projections and form a climate scenario. Finally, the impact of the climate scenario on the hydrological system can be translated by WaterVision to impacts on flora and nature objectives.

4. Materials and methods

4.1 Modelling related steps – general

TAUW made a comprehensive model of Punthuizen-Stroothuizen using iMOD (Chapter 3). Three model runs were executed: baseline conditions (model 1), short-term measures (model 2) and long-term measures (model 3). Model 1 reflects the average system and the general groundwater levels in Punthuizen-Stroothuizen. The short-term measures focus on the reduction of drainage in and around Punthuizen-Stroothuizen and the reduction of depth in tributaries of the Dinkel (Provincie Overijssel, 2017). This is done by removing water pipe drainage, removing drainage ditches and leggerwatergangen[12] and decreasing the depth of waterways (Bor, 2018). The long-term measures include the short-term measures in combination with a water level increase of the Puntbeek and the removal of German drainage ditches.

The three models simulate 10226 daily time steps, starting at January 2nd 1975 and ending at December 20th 2002. Daily precipitation and reference evaporation data is used and daily well abstraction is included from 1989. This period stays constant during this research since the model is calibrated on this period of time and changes may result in decreased accuracy. The input files included in the river- and drainage package are changed to model the impact of the measures. The rest of the model stays the same.

Per scenario, the GXGs are retrieved from the model using a short script provided by TAUW and displayed in maps for Punthuizen-Stroothuizen and its surroundings. The GHG is calculated by extracted the three highest measured groundwater levels (HG3) per hydrological year (1st of April to 31st of March). The GHG is the average of the HG3s over the measurement series. The same method is used to calculate the GLG, but now using the lowest measured groundwater levels. The GVG is calculated using the groundwater levels on the 14th of March, 28th of March and 14th of April. On top of that, the differences between those maps is calculated to show the effects of the measures on the groundwater levels. Despite this research's focusses on droughts in summer, results for the winter are shown throughout this report. This is done because of the influence of winter groundwater levels on summer circumstances. When groundwater levels in summer drop quite deep, more precipitation is needed to bring winter groundwater levels high enough and the other way around.

Point data is retrieved from the model at the location of monitoring wells. For Punthuizen this are monitoring wells B29C0243, B29C0245 and B29C0252. For Stroothuizen this are monitoring wells B29A0191, B29A0199, B29A0204 and B29A0208. All monitoring wells are coupled to a specific vegetation type according to the maps in Appendix 2. This is the first selection criteria. For *zwakgebufferde vennen* and *pioniersvegetaties,* only one monitoring well was available for each type. These therefore were selected right away. In Punthuizen, only *blauwgrasland, droge heide and vochtige heide* can be found. However, there is no monitoring well located in *droge heide*. Two different monitoring wells were selected for *blauwgrasland,* one in the low-laying area and one at a somewhat higher location. For Stroothuizen, only one monitoring well is located in *vochtige heide*. The monitoring well for *blauwgrasland* is chosen since it's the lowest in Stroothuizen.

Different vegetation types reflect different elevation levels, since all habitat types have their own optimal hydrological conditions. For example, *zwakgebufferde vennen* is located at the lowest elevation, since this type needs inundation.

Time-hydraulic-head-lines were retrieved to see how the measures impact the groundwater levels throughout time. Using the information of this section, we answered sub questions 1 and 2.

[12] Large channels/rivers managed by water boards.

4.2 Modelling related steps – climate change

The model did not include projections for the future. The most extreme scenario (W_h) of the KNMI formed the basis for the climate predictions. The daily precipitation- and evaporation grids were downloaded from the KNMI Datacenter for the years 1973 until 2003 (KNMI Datacenter, 2016; KNMI Datacenter, 2016a). These datasets contained daily grids saved in NetCDF-files. These NetCDF-files were converted to ASCII-files, since the model can only read ASCII-inputfiles. This conversion is done using climate4impact.eu. Afterwards, the mete_grid.inp file was changed to include the scenario grids into the model. The rest of the model stayed the same. The initial situation and both short- and long-term measures were modelled including the climate scenario.

The data generated by the model was translated into useful datatypes by different postprocessing tools in the possession of TAUW. Difference maps visualize the effect of the measures and climate change. Also, the time-hydraulic-head-lines were used to see changes in seasonal patterns.

Fluxes were determined for the location of the monitoring wells as well. This was done because higher fluxes are needed to cope with acidification and to make sure base-enrichment of groundwater is as high as possible. The fluxes were calculated in winter, spring and summer. To calculate fluxes for each season, fluxes on three days[13] were extracted from the daily data for a specific year. Those three fluxes were averaged into a spring, winter and summer flux for the years 1989 until 2001 for each point. These yearly-seasonally fluxes were plotted over time for all six scenarios to see the effects of the measures and climate change on the fluxes in the area.

Using information gathered in this section, we can answer subquestion 3.

4.3 Relative survival chances of nature

The last part of the study focusses on the impact on nature. The different vegetation types are sensitive to groundwater level, time span of inundation and base enrichment (Paragraph 2.2). However, not all vegetation types are sensitive to all those factors. Which vegetation types are sensitive to which factors and values of optimal GXG conditions is based on literature research and survival chances were based on whether optimal conditions of those factors are met.

From the groundwater model, point data was extracted at the coordinates of the monitoring wells mentioned above. First of all, the difference in GLG and GVG between the baseline conditions and the scenarios were extracted. These values display the effect of measures and/or climate change at that specific point. Using these values, 'doelgaten' were calculated of each scenario. A *doelgat* is the difference between the scenario GLG or scenario GVG and the optimal values (Table 4) and displays whether the groundwater level is sufficiently high for a specific vegetation type. The baseline GVG and GLG were based on table 3 and 4 from Dongen, et al. (2017). These values are more accurate and more recent than values from the groundwater model. The model output is therefore only used for effect calculations.

[13] Winter: 28th of December, 14th of January, 28th of January
Spring: 28th of March, 14th of April, 14th of May
Summer: 14th of July, 28 of July, 14th of August

*Table 4: Optimal GXG-conditions for habitat types. *source: Dongen et al. (2017). ** source: Alterra, KWR, & STOWA (2014)*

Monitoring well	Habitat type	Area	GLG	GVG, upper	GVG, lower
B29C0252	Blauwgraslanden	PH	0.9*	0.05*	0.22*
B29C0245	Blauwgraslanden	PH	1*	0.02*	0.15*
B29C0243	Vochtige heide	PH	1.5**	-0.02*	0.25*
B29A0208	Zwakgebufferde ven	SH	0.7*	-0.35*	-0.1*
B29A0204	Pioniersvegetaties met Snavelbiezen	SH		-0.1**	0.4**
B29A0199	Vochtige heide	SH	1.5**	-0.02*	0.25*
B29A0191	Blauwgraslanden	SH	0.7*	-0.35*	-0.1*
	Droge heide			0.5**	

Which vegetation type belongs to which monitoring well was based on the maps shown in Appendix 2. However, Table 4 shows that not all vegetation types are represented in one of the monitoring wells. For *droge heide* therefore we looked at GVG values from WaterVision since *droge heide* is only vulnerable to high groundwater levels.

Time-span of inundation is visible in duration-lines. These lines display how often groundwater levels exceed a given value. Finally, we looked into the fluxes again, since base enrichment depends on seepage fluxes.

From the point data gathered at the monitoring wells, we zoomed out using WaterVision, which is used to model whether climate change may impact the different vegetation types throughout Punthuizen-Stroothuizen. The WATERNOOD-tool is used to calculate the *doelgat* per pixel for the GVG and GHG. WaterVision thus used the same method as described above, but on a pixel basis. PROBE is used to model transpiration[14]- and oxygen stress[15] target realization maps, which are used to complement the GVG and GHG-*doelgaten.* Transpiration- and oxygen stress maps calculated more 'climate robust' factors for the availability of moisture and oxygen (Witte, et al., 2018). GVG, GLG, transpiration stress and oxygen stress-maps were chosen since they give the most information about the effect of changes in groundwater level on specific species.

To use WaterVision, different input maps were needed. Hydrological input (GXGs and seepage maps) for WaterVision was extracted from the different model runs. Next to that, the location of the area was needed, which was easily extracted from the Natura 2000 shapefile of the European Environmental Agency (European Environmental Agency, 2017). Also, to test the vegetation objectives, a map with nature objectives/habitat types was needed. The five different habitat types shown in Table 1 were included. The original polygon map is transferred to a raster-map with 25x25m grids. Afterwards, from this map the pixels belonging to one habitat type were extracted, resulting in 5 different maps. This is done so more detailed information could be extracted since only one vegetation type is visible instead of information about all different vegetation types in one map. All input files need to have a resolution of 25x25 meters.

WaterVision uses a '*knikpunten-tabel'* in which optimal groundwater levels are stated. The same optimal hydrological conditions are used for the point data as for the WaterVision-grid-data. For *Blauwgrasland,* different values are used for point-data analysis. These values were averaged for usage in WaterVision.

After the completion of the input files, six model runs were executed, all in- and excluding climate change: the initial situation, short-term measures and long-term measures.

[14] Transpiration stress reflects a moisture shortage in the rootzone when groundwater levels are too low in summer
[15] Oxygen stress reflects a oxygen shortage in the rootzone when groundwater levels are too high in spring

5. Results

5.1 Groundwater levels under baseline conditions

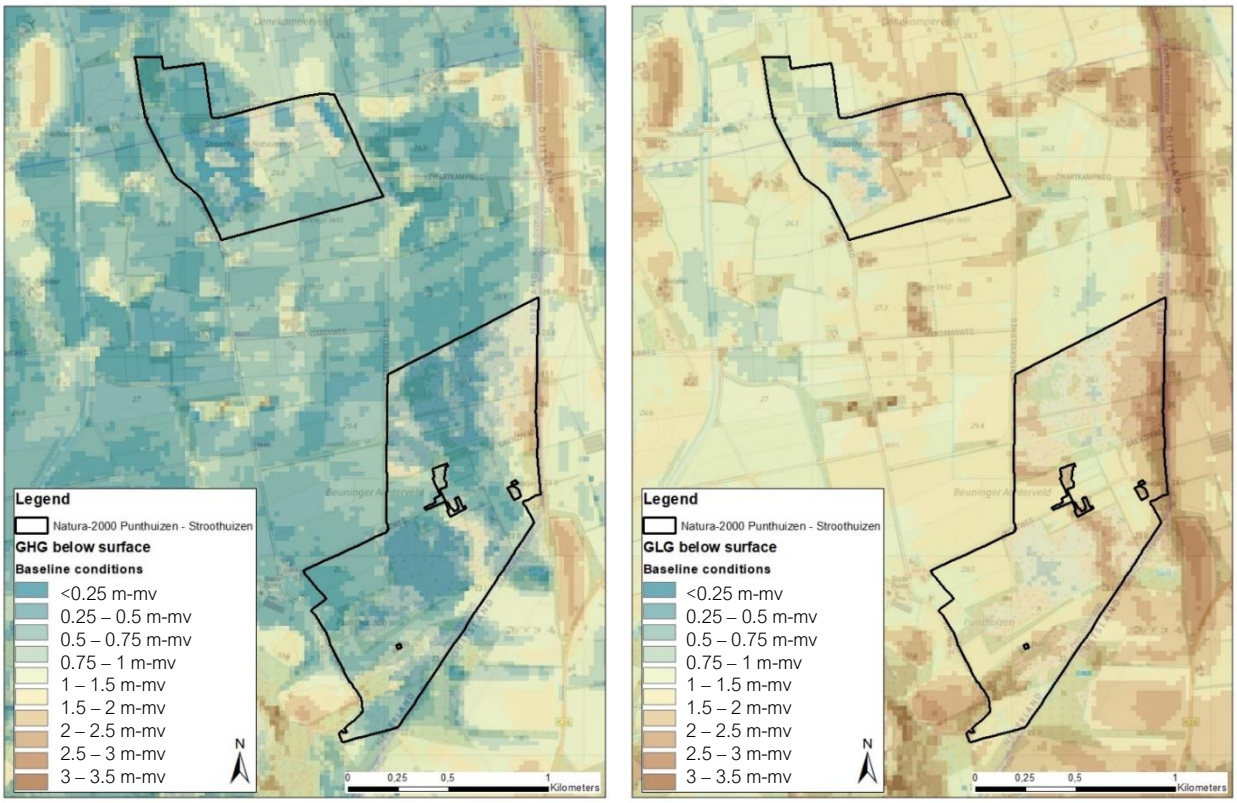

Figure 6: GHG (left) and GLG (right) under baseline conditions

Long-term average groundwater levels in winter (left) indicate groundwater levels close to surface in some parts of Punthuizen-Stroothuizen (Figure 6). Long-term average groundwater summers in summer (right) display deep groundwater levels in some areas, for example in the eolian sand ridges on the German border (Figure 6).

The time-hydraulic-head line for monitoring well B29C0252 clearly shows inundation in winter in the measurement points, since this one is located in one of the low-laying parts of Punthuizen (Appendix 3). The same accounts for B29A0191 and B29A0208. For these points, the graphs also show groundwater levels closer to the surface in summer. For the higher located monitoring wells, measurements show lower groundwater levels in winter and deeper levels in summer in comparison to the lower located monitoring wells. These patterns are also displayed Table 5.

Table 5: Selected monitoring wells with their surface elevation and GxG's under baseline conditions (table 3 in Dongen, et al. (2017))

Monitoring well	Area	Habitat type	Surface elevation (m above NAP)	GHG (m below surface)	GLG (m below surface)
B29C0252	Punthuizen	Blauwgraslanden	28.42	-0.18	1.1
B29C0245	Punthuizen	Blauwgraslanden	28.79	0.1	1.42
B29C0243	Punthuizen	Vochtige heide	28.81	0.13	1.51
B29A0208	Stroothuizen	Zwakgebufferde ven	25.40	-0.09	0.63
B29A0204	Stroothuizen	Pioniersvegetaties	25.88	-0.05	0.62
B29A0199	Stroothuizen	Vochtige heide	25.69	0.02	0.73
B29A0191	Stroothuizen	Blauwgraslanden	25.17	-0.15	0.53

5.2 Effect of proposed measures of 2017 on groundwater levels

5.2.1 Short-term measures

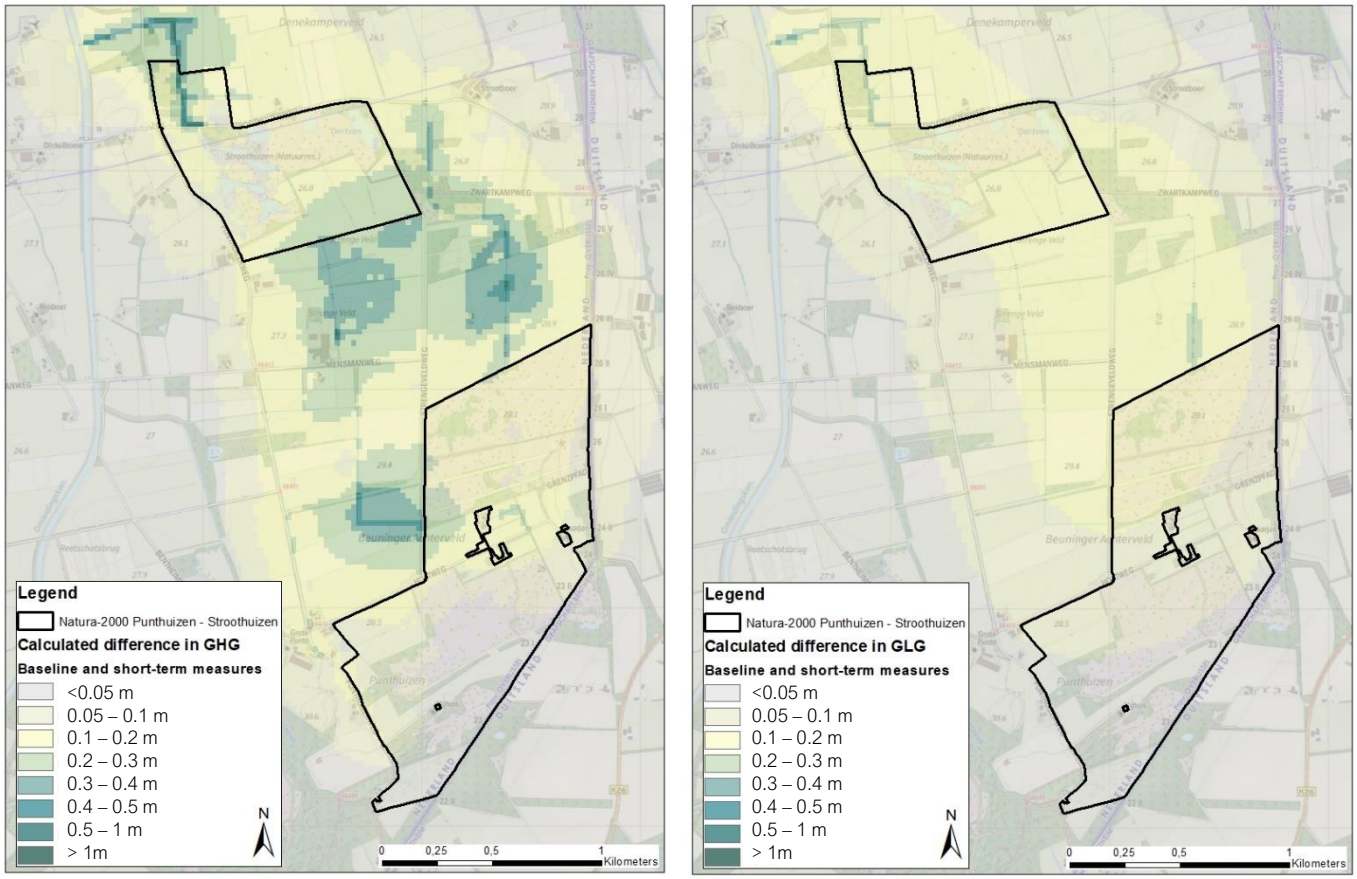

Figure 7: Calculated difference in GHG (left) and GLG (right) due to short-term measures

The largest effect of the short-term measures are found in between Punthuizen and Stroothuizen and in the northern part of Stroothuizen (Figure 7). This is mainly due to the removal of water pipe drainage and the removal/decreasing of depth of drainage ditches. In the northern part of Stroothuizen, an important drainage ditch is removed. Higher groundwater levels are expected for both summer and winter.

5.2.2 Long-term measures

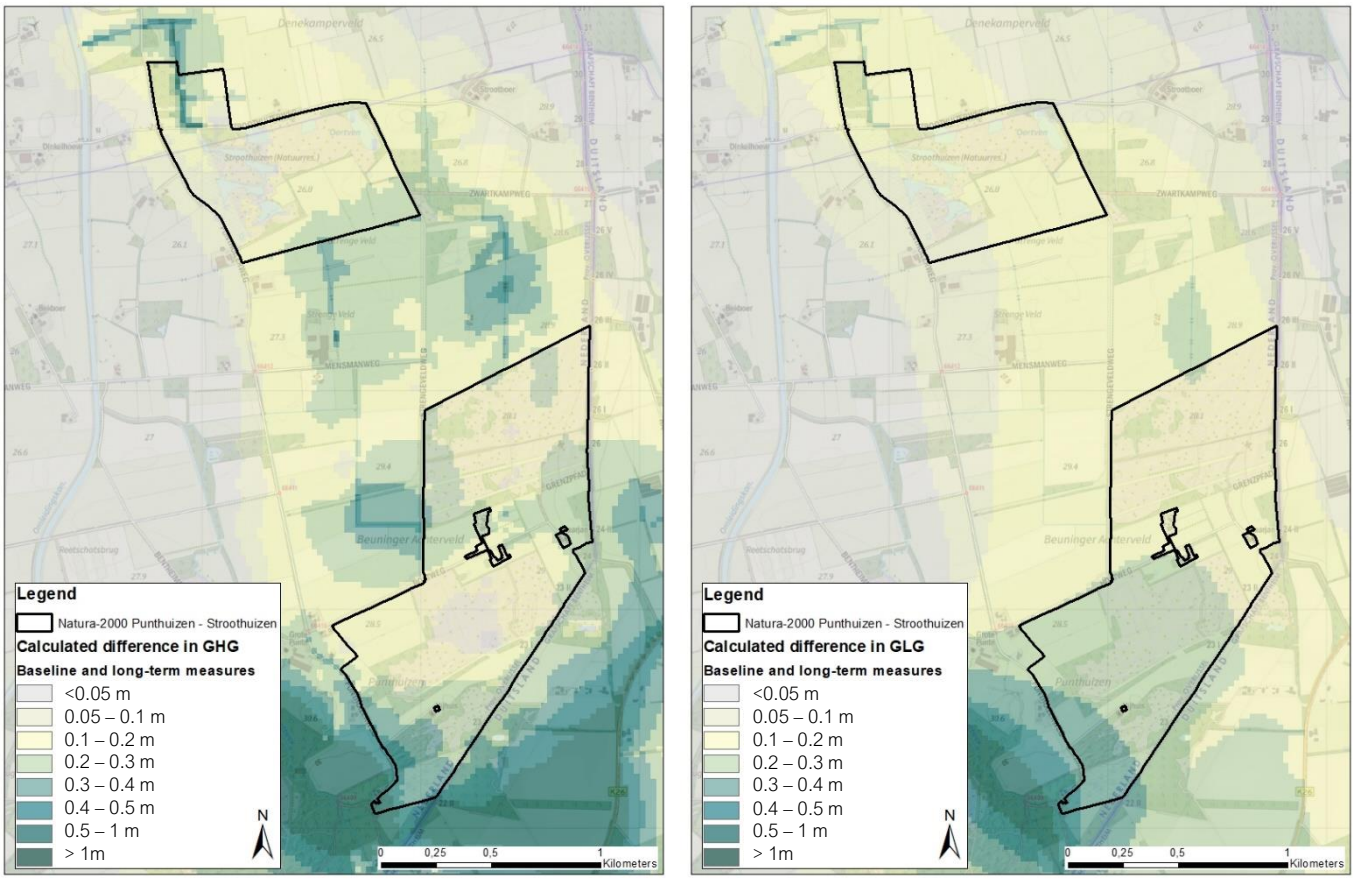

Figure 8: Calculated difference in GHG (left) and GLG (right) due to long-term measures

Large increases of groundwater level are found south of Punthuizen, due to the removal of German drainage ditches and an increase of the water level in the Puntbeek (Figure 8). The increase of the Puntbeek's waterlevel is also clearly visible in the GLG.

The time-hydraulic-head-lines in Appendix 3 also clearly show the effects of the measures. Higher groundwater levels are shown in both winter and summer. However, for most monitoring wells in Stroothuizen, the difference between the long-term and short-term measures is small. In Punthuizen, the difference is somewhat bigger and the long-term measures show higher groundwater levels than the short-term measures. This is in line with Figure 7 and Figure 8. On top of that, most monitoring wells are located in areas where measures do not have large effects like in the most southern point of Punthuizen. Therefore little difference in long- and short-term measures is visible. Again, higher groundwater levels in both summer and winter are beneficial to cope with climate change.

5.3 Climate change and its effects on the hydrological system

5.3.1 Groundwater levels

Effect of climate change on GHG and GLG

Figure 9: The effect of climate change on the GHG (left) and GLG (right) under baseline conditions

Winter precipitation increases in the W_h-scenario. Climate change has relatively little impact in winter since only changes between -5 and +5 cm are found in the area (Figure 9). The small decrease in groundwater level is likely to be caused by the drainage of groundwater by drainage ditches. Also, the abandoned river branches in the western part of Stroothuizen and a low-lying area in the middle of Punthuizen are clearly visible. These parts inundate in winter. When the water level reaches a certain height, water can flow over a natural threshold, leading to overland flow. Therefore, the water level here cannot increase more than this level. Also, when looking into the time-hydraulic-head lines in Appendix 3, the differences in winter are nihil.

Bulging increases in the eolian sand ridges due to the infiltration of precipitation, for example near the German border and the area southeast of Punthuizen. So in general, in areas where drainage or a thin unsaturated zone is present, a small decrease in GHG is expected. In areas where drainage is limited and/or a thicker unsaturated zone is present, more bulging is expected.

Groundwater levels decrease up to 20 cm in summer, which is a logical consequence of a decrease in summer precipitation (Table 3), and is clearly visible in the graphs of Appendix 3. However, the decrease is smaller in the areas near the border of Germany and southwest of Punthuizen (5 to 10 cm). In summer, the groundwater level in these areas is lower than the other parts and drought stress is already a problem. Thus, evaporation by vegetation may not increase in these areas. In the areas where groundwater decreases more (10 – 20 cm), evaporation may increase more. This is a possible explanation for the larger decrease of groundwater level in some parts of the area.

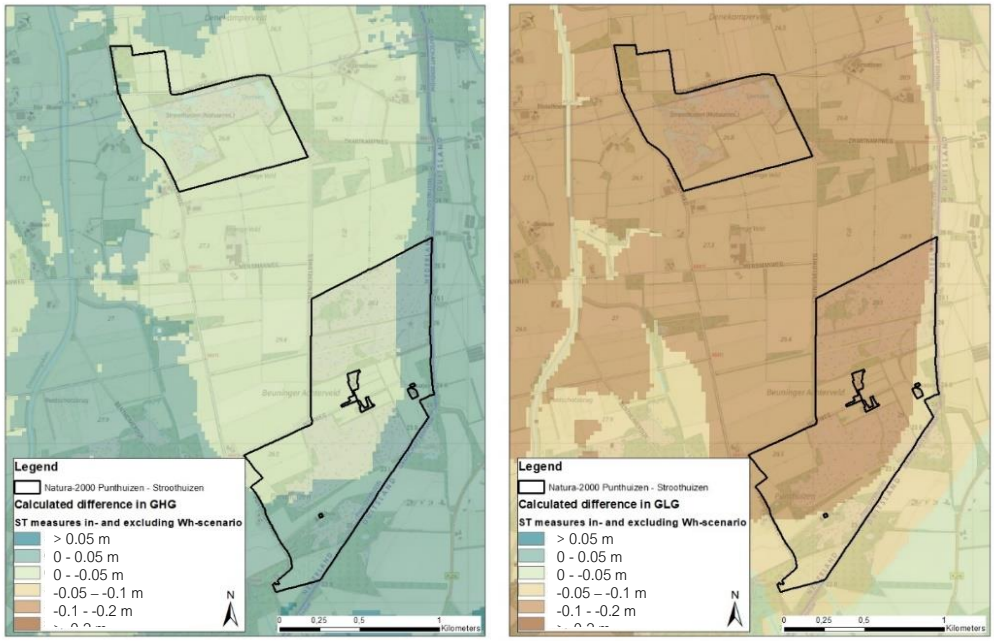

Figure 10: The effect of climate change on the GHG (left) and GLG (right) including short-term measures

Climate change effects for short-term measures (Figure 10) are similar when including the short-term measures. Short-term measures lead to increasing groundwater levels (Figure 7), the unsaturated zone became thinner.

The broad pattern in GHG is similar to Figure 9. However, a larger area experiences a relatively small decrease of the GHG than displayed in Figure 9. Groundwater levels are higher and closer to the surface due to the reduced drainage by measures. Thus, in the areas with a small decrease 'no space' may be left for more bulging. In the infiltration areas in the east and southwest, space is left for extra bulging, so an increase of groundwater level is still possible.

Also the area with a 0.1 to 0.2 m decrease in GLG is larger when including the short-term measures. Measures increased summer groundwater levels, so more water is available for vegetation. Evaporation may increase in the areas where the groundwater level is still relatively close to the surface, resulting in a lowering of groundwater levels.

The same patterns are also shown when looking at the long-term measures for GHG and GLG (Figure 11) and the same explanations can be used to explain those images. In winter, the groundwater level is already high and cannot increase more in some areas. In summer, evaporation can increase, resulting in larger areas with a declining groundwater level.

Figure 11: The effect of climate change on the GHG (left) and GLG (right) including long-term measures

Effect of climate change and measures on GHG and GLG

Groundwater levels are increasing in winter, when we compare the baseline conditions with short-term measures in combination with climate change (Figure 12). The area thus gets wetter in winter due to the effects of both measures and climate change.

In summer, the increase of groundwater level due to the measures (Figure 7) is combined with a decrease of groundwater level due to climate change. The measures are not sufficient for most of the area since a decrease is still shown. Thus, the short-term measures have a positive effect in winter, but in summer these are not enough to compensate for the effects of climate change.

Figure 12: The effect of climate change in combination with short-term measures on the GHG (left) and GHG (right)

The long-term measures combined with climate change result in increasing groundwater levels for both Punthuizen and Stroothuizen in winter (Figure 13). The effects in the southern parts are bigger in Figure 13 than in Figure 12 for both GHG and GLG. Here the effects of the extra measures included in the long-term scenario are clearly visible. For the summer, the extra measures included in the long-term scenario are resulting in an increase of groundwater level in Punthuizen. For Stroothuizen, still a decline in groundwater level is expected. Although, this is at most 10 cm.

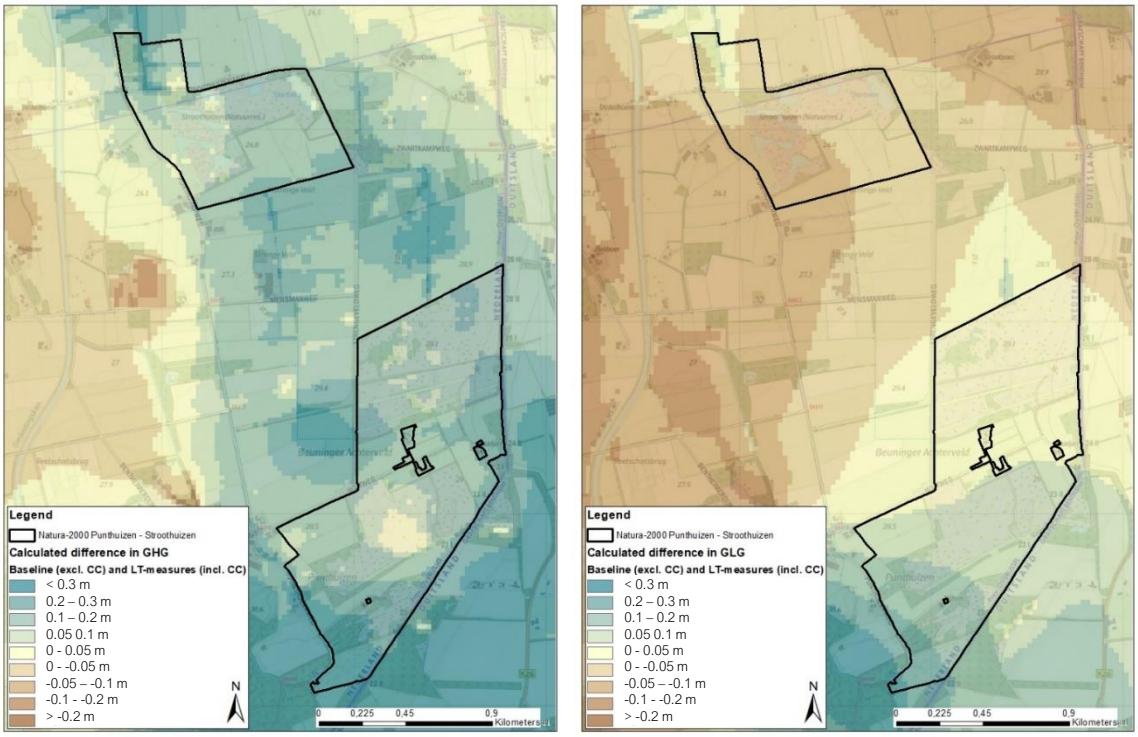

Figure 13: The effect of climate change in combination with long-term measures on the GHG (left) and GLG (right)

The last two figures show the most interesting results. Both the short- and long-term measures result in higher GHGs when combining it with climate change. Measures therefore have enough impact in winter. However, the average groundwater levels are expected to drop in summer for the entire area (short-term) and for Stroothuizen and surrounding areas (long-term). The measures reduce the negative effects of climate change, but do not lead to enough groundwater level increase in Stoothuizen to neutralize the effect.

Two effects become clear when studying the time-hydraulic-head lines in Appendix 3. First of all, the effect of climate change is mostly visible in summer, leading to lower GLGs. Second, the measures increase groundwater levels mainly in winter.

5.3.2 Fluxes

In Punthuizen-Stroothuizen, it is important to see increasing fluxes in winter and spring due to the measures and/or climate change. Higher fluxes means more drainage in the area. When drainage is higher, the area is wetter, and the chance of base enriched seepage gets bigger. This base-enriched seepage is important for the vegetation in the area and ensures that acidification of the area decreases. Appendix 4 shows per monitoring well six different graphs: the effect of climate change on winter, spring and summer fluxes and the effects of measures and climate change on winter, spring and summer fluxes. The effects shown in those graphs will here be described.

Punthuizen

Monitoring wells B29C0243, B29C0245 and B29C0252 are used to evaluate the changes in fluxes in Punthuizen. In normal years, the base enrichment of groundwater reaches 100%, but during dryer years, it only reaches 60 to 70%. This results in lower base enriched and lower fluxes and less buffer against the acidification. The system is therefore vulnerable to dry years.

Monitoring well B29C0243 is located in relatively high elevated infiltration area, with very local seepage and groundwater flow. Infiltration occurs throughout the year in normal and dry years. In years like 1994 and 1995, the amount of winter precipitation was relatively high and bulging increased. In these years, seepage can occur and increases due to climate change. Figure 14 shows little changes for climate change in normal winters, when infiltration dominates. With respect to the measures, these have relatively low impact in normal years in winter in this place. In wet years, when seepage is expected, measures (in combination with the W_h-scenario) increase this effect in winter. In spring almost all fluxes are infiltration fluxes. Only the long-term measures change infiltration to seepage in some years, but these also let infiltration fluxes increase in some years. With respect to summer, all fluxes remain infiltration fluxes. It differs per year whether they are higher or lower than under baseline conditions.

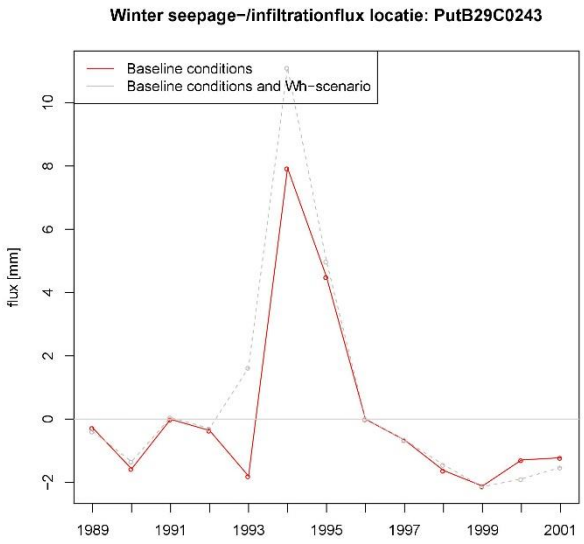

Figure 14: Average winter flux (in mm per day) per year for baseline conditions and baseline conditions and Wh-scenario

Monitoring well B29C0245 is located in an area where seepage is dominant. For almost all years, climate change and measures increase seepage on this place. This is a positive effect, because in this area circumstances where suboptimal, but become better now since also the spring fluxes increase substantially in most years. In some years, fluxes even double. Again, long-term measures have the most impact in combination with climate change. In summer, climate change results in a change from infiltration to seepage in some years. The effects of the measures and climate change on this point are very beneficial.

Monitoring well B29C0252 is located in the lowest part of Punthuizen and is inundated in most winters. In wet years like 1993 and 1994 small increases in fluxes are found. The effect of the measures and climate change is most visible in the normal to somewhat dry years like 1998 to

2001. In wet years, the base enrichment of the groundwater is sufficient but the higher fluxes in the normal to dry years are beneficial for the base-enrichment and thus the system.

Stroothuizen
Monitoring wells B29A0191, B29A0199, B29A0204 and B29A0208 are used to evaluate the changes in fluxes in Stroothuizen. Current fluxes in Stroothuizen are too low, resulting in acidification. Increase in fluxes is therefore crucial.

Monitoring well B29A0191 is located in one of the old low-lying river branches in Stroothuizen. Again, winter and spring fluxes increase more in normal years than in wet years, which is beneficial. In summer, climate change brings extra seepage. These patterns are plausible, since the infiltration on the higher eolian sand ridges increases. This results in more flow towards the lower areas. With respect to the different scenarios, the short-term measures (in combination with climate change) have the most effect. The long-term measures have relatively little extra effect here.

Monitoring well B29A0199 is located higher in the system and shows a somewhat different trend. This spot is wet in winter, but groundwater levels drop in summer. In wet years, fluxes change from small to quite high. This is due to the bulging in the eolian sand ridges, resulting in flow towards the low-lying areas in wet years, also in spring.

Monitoring well B29A0204 has the highest elevation of the selected monitoring wells in Stroothuizen. Originally, drainage and eutrophicated groundwater inflow were problematic here. Influence of base enriched groundwater flow is to small here. In winter and spring, all scenarios bring higher fluxes, which is beneficial for this spot. Again, climate change brings higher fluxes.

Monitoring well B29A0208 is, just like 191, located in one of the low-laying abandoned river branches and shows also roughly the same patterns. Winter fluxes in wet years show relatively less differences, while in normal years seepage increases.

Overall, winter and spring fluxes are increasing, which is a positive sign.

5.4 Wrap up

Both short- and long-term measures have effects on groundwater levels throughout the year. Only small differences between effects of short- and long-term measures are visible for Stroothuizen. For Punthuizen, the effects of the long-term measures are larger.

Secondly, climate change has only small effects (-5 to +5 cm) in winter throughout the area. The area that shows a small decrease (-5 cm) in GHG broadens when including measures, since it is likely that groundwater levels are close to the surface. Groundwater levels decrease with 5 to 20 cm in summer. The measures enlarge the area with a decrease in GLG of 10 to 20 cm increases due to increased evaporation possibilities. However, the impact of climate change in summer is 20 cm at max, regardless of whether the measures are implemented or not.

Third, groundwater levels are increasing throughout the area in winter due to both climate change effects and measures. However, a decrease in groundwater levels is still visible in Stroothuizen for both short- and long-term measures in summer. For Punthuizen, an increase in GLG is visible for the long-term measures but not for the short-term measures.

Both climate change and measures bring increasing fluxes in winter and spring, which is beneficial.

5.5 Effect of climate change on flora

The different vegetation types are sensitive to different factors like GVG, GLG, fluxes and inundation. The first part of this chapter consist of information on the different vegetation types and which factors they are vulnerable to, summarized in Table 6.

The GVG is important for all the different vegetation types of Punthuizen-Stroothuizen. The GLG is less important to some vegetation types than the GVG. For example, *droge heide* can cope with quite deep groundwater levels in summer and even need some drought in summer (Alterra, KWR, & STOWA, 2014). *Pioniersvegetaties met Snavelbiezen* also does not need a GLG value according to Alterra, KWR & STOWA (2014).

Zwakgebufferde vennen is the most critical type that needs inundation and due to too short inundation periods, quality decreased (Dongen, et al. 2017). *Pioniersvegeaties met Snavelbiezen* also needs some inundation (Alterra, KWR, & STOWA, 2014), but is less dependent on inundation than *zwakgebufferde vennen*. The other vegetation types are not dependent on inundation.

Seepage is the most important for *Blauwgrasland,* since it needs base enriched groundwater. *Blauwgrasland* can be found on the edge of low-lying areas, just above inundation levels. Seepage is largest in winter and subassociations of *Blauwgrasland* can be found here (Dongen, et al., 2017). *Zwakgebufferde vennen* also needs seepage, since 'it needs clean, buffered groundwater via seepage' (Ministerie van Landbouw, 2019c). The other vegetation types grow in more acidic conditions, so don't need base enriched seepage.

Table 6: Sensitivity of vegetation types to different hydrological factors (+ means this factor is important for the vegetation type)

Vegetation type	GVG	GLG	Inundation	Fluxes/seepage
Blauwgrasland	+	+		+
Zwakgebufferde vennen	+	+	+	+
Pioniersvegetaties met snavelbiezen	+		+	
Vochtige heide	+	+		
Droge heide	+			

Now that we know which factors we should take into account for each vegetation type, we can look into those specifically, but first we will look into the current situation. Afterwards, the impact of measures and climate change on GXGs, inundation and fluxes will be discussed.

5.5.1 Current situation

Dongen, et al., (2017) states that groundwater levels in the period 2002 to 2010 where considerably lower than in the '90s in Punthuizen. The difference between the two periods is approximately 20 cm in summer and 5-15 cm in winter. Groundwater levels were already at the edge or just below the optimum range in the 90s, so the *doelgat* increased. Table 7 shows the *doelgaten* for the monitoring wells, which reflect this effect.

The GXGs for the different scenarios are compared with optimal GXGs for the habitat types to get the *doelgaten*. When the scenario GXG is lower than the optimal GXG, the *doelgat* is displayed with a minus and in red in the table, since groundwater levels are too low. When the scenario GXG is higher than the optimal GXG, the value is displayed in green. The GXGs for the baseline conditions are retrieved from table 2 and 3 from Dongen, et al. (2017).

The inundation period is decreased from 20-35% in the 90s to 5-25% in the period 2001-2016. Optimal values for inundation are between 20 and 60%. Vegetation types decreased in coverage

and quality due to these dryer circumstances. For Punthuizen, it is necessary that duration of inundation increases, just like GVGs and GLGs to make sure hydrological conditions become more optimal for the different vegetation types.

For Stoothuizen, the difference in groundwater level between the period of 1989 and 2001 and 2001 and 2016 are smaller than in Punthuizen, approximately 0 to 10 cm for all seasons. In Stroothuizen, most monitoring wells score well with respect to *doelgaten*. Desiccation is not an important bottleneck, but low fluxes are, resulting in low base enrichment. This results in acidification. Especially *zwakgebufferde vennen* and *blauwgrasland* are affected.

Table 7: Doelgaten baseline conditions

			Doelgat baseline	
Well	Habitattype	Area	GLG	GVG
B29C0252	Blauwgraslanden	Punthuizen	-0.20	0.19
B29C0245	Blauwgraslanden	Punthuizen	-0.42	-0.13
B29C0243	Vochtige heide	Punthuizen	-0.01	-0.07
B29A0208	Zwakgebufferde ven	Stroothuizen	0.07	-0.12
B29A0204	Pioniervegetaties met Snavelbiezen	Stroothuizen		0.35
B29A0199	Vochtige heide	Stroothuizen	0.77	0.12
B29A0191	Blauwgraslanden	Stroothuizen	0.17	-0.07

5.5.2 Effects of climate change and measures on flora

Groundwater levels

Table 8 shows per monitoring well the *doelgaten* for each scenario. The baseline conditions are retrieved from Dongen, et al. (2017). The modelruns only display the increase/decrease in groundwater levels caused by the measures and/or climate change. With the increase/decrease values can be stated whether the groundwater levels come closer to the optimal groundwater levels or not. The *doelgat* determination for vegetation types represented by monitoring wells is easy since point values can be compared. Appendix 5 shows an extended version of Table 8, with baseline values and all increase/decrease values.

Table 8: Doelgaten per scenario per monitoring well/vegetation type. ST = short term measures. LT = long term measures

			Doelgat baseline		Doelgat baseline + wh		ST		ST + Wh		LT		LT + Wh	
Well			GLG	GVG	GLG	GVG	GLG	GVG	GLG	GVG	GLG	GVG	GLG	GVG
B29C0252	Blauwgraslanden	PH	-0.20	0.19	-0.31	0.16	-0.14	0.23	-0.27	0.19	0.02	0.29	-0.14	0.24
B29C0245	Blauwgraslanden	PH	-0.42	-0.13	-0.52	-0.16	-0.37	-0.10	-0.48	-0.14	-0.20	-0.05	-0.35	-0.09
B29C0243	Vochtige heide	PH	-0.01	-0.07	-0.11	-0.09	0.05	-0.02	-0.07	-0.05	0.20	0.06	0.05	0.02
B29A0208	Zwakgebufferde ven	SH	0.07	-0.12	-0.07	-0.16	0.17	-0.03	0.01	-0.07	0.16	-0.03	0.00	-0.07
B29A0204	Pioniervegetaties met Snavelbiezen	SH		0.35		0.31		0.44		0.40		0.44		0.39
B29A0199	Vochtige heide	SH	0.77	0.12	0.64	0.10	0.88	0.23	0.73	0.20	0.88	0.22	0.73	0.19
B29A0191	Blauwgraslanden	SH	0.17	-0.07	0.04	-0.10	0.29	0.02	0.13	-0.01	0.29	0.02	0.12	-0.02

Climate change results in a lowering in GLG of 10.5 to 13.5 cm. For GVG this is 1.5 to almost 4 cm. The effects of climate change on groundwater levels are thus negative for the habitat types. Table 8 shows again that both the long- and short-term measures were proven to be effective. Due to the short-term measures, groundwater levels in summer increase 5 to 11 cm. In spring,

this is 4 to 11 cm. Due to the long-term measures, groundwater levels even increase 9 to 22 cm in summer and 8 to 11 cm in spring.

Optimal conditions for *blauwgrasland* are shown by monitoring well B29C0252 in summer and spring, when including the long-term measures. However, due to climate change summer groundwater levels decrease again. Also in the low-laying area in Punthuizen (well B29C0245), groundwater levels still are to low and again, climate change neutralizes the effects of the measures. However, the picture is somewhat brighter around monitoring well B29C0243 for *vochtige heide*. Despite climate change, groundwater levels stay high enough when including the long-term measures.

In Stroothuizen desiccation is not as big as a problem as in Punthuizen. Climate change result in lower groundwater levels but does not show an increase of vegetation types where groundwater levels become sub-optimal. *Zwakgebufferde vennen* however has almost no space left before groundwater levels become suboptimal.

Climate change lowers groundwater levels and measures are needed to cope with climate change and bring some extra space for some vegetation types, but cannot increase groundwater levels enough to reach optimal groundwater levels for all vegetation types when taking into account climate change. Extra measures are necessary for some vegetation types.

Inundation

Inundation is only necessary for *zwakgebufferde vennen* and *pioniersvegetaties met snavelbiezen*. Duration-lines are extracted from the model data, at the location of the monitoring wells, to check whether more inundation is expected. Duration-lines show how often (in percentage) a specific head is exceeded. The green horizonal line displays the surface elevation. When the head is higher than the surface elevation, inundation takes place. Under baseline conditions inundation therefore takes place approximately 24% of the time for monitoring well B29A0204 (Figure 16). Climate change results in a shorter inundation time. This is remarkable since groundwater levels stay roughly the same in winter and precipitation increases.

However, due to the measures, the time inundation takes place increases quite a lot. The duration lines of the long- and short-term measures differ so little that the short-term duration line is not visible.

The same pattern for *zwakgebufferde vennen* (Figure 15). Inundation there increases from approximately 32% to approximaltey 42% including measures and climate change. Again, the measures are needed to come closer to optimal hydrological circumstances.

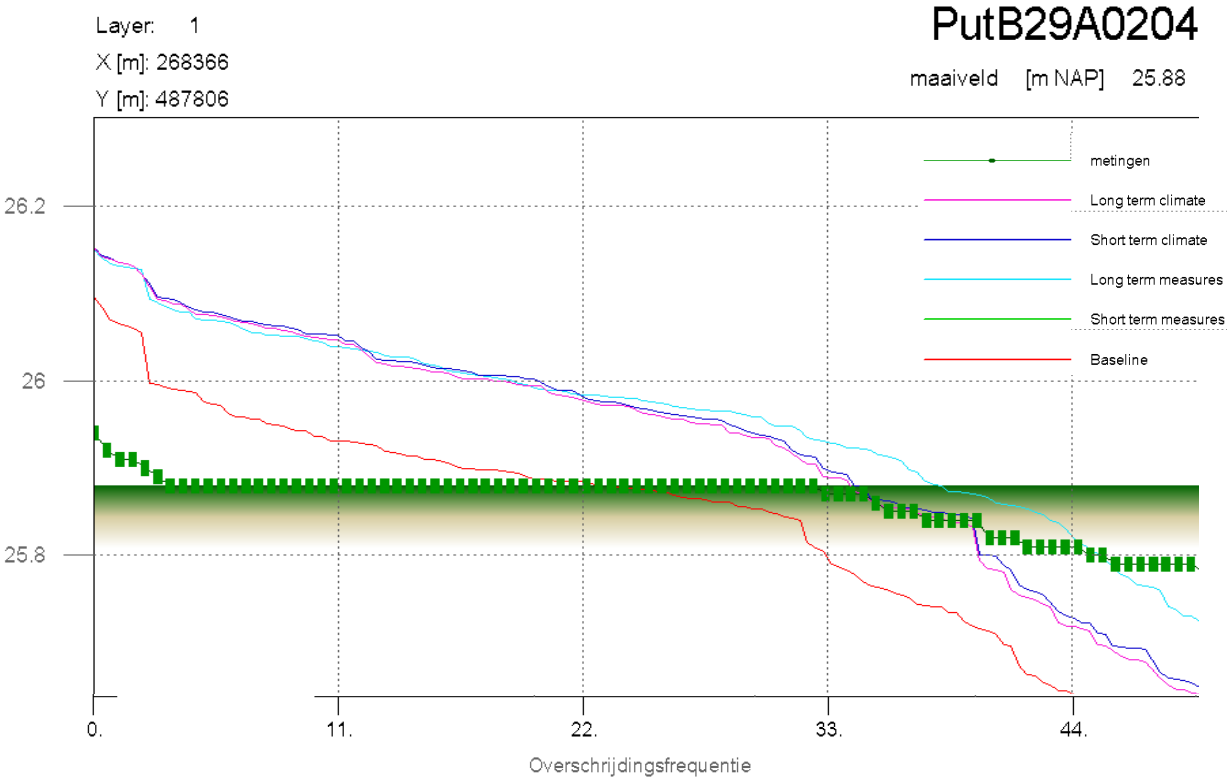

Figure 16: Duration line of monitoring well B29A0204, Pioniersvegetaties met Snavelbiezen

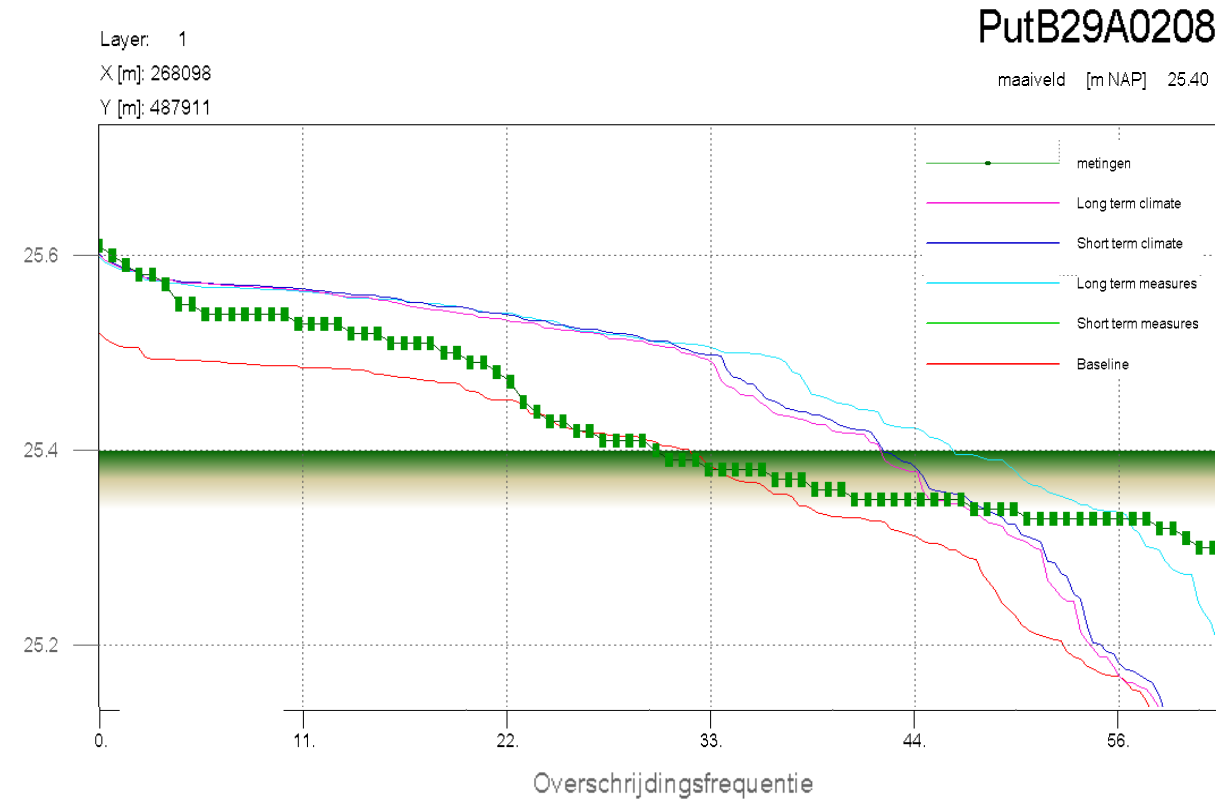

Figure 15: Duration line of monitoring well B29A0208, Zwakgebufferde vennen

Fluxes and seepage
For *zwakgebufferde vennen* and *blauwgrasland,* base enriched seepage is an important hydrological factor. Seepage is a upward flux and when there is hardly any seepage, base enrichment decreases (Dongen, et al., 2017). So, the extent to which seepage occurs, influences the base enrichment in the root zone and in inundated fens. Larger upward fluxes are important for those vegetation types since base enrichment decreased in the past and in the current situation, there is not enough base enrichment.

Upward fluxes increase in winter and spring due to both climate change and measures for monitoring well B29C0245 (Paragraph 5.3.2). For monitoring well B29C0252 the largest increases were found in normal to somewhat dry years. This is also the case for monitoring well B29A0191. For *blauwgrasland,* the effects of measures and climate change is beneficial with respect to base-enrichment.

For *zwakgebufferde vennen* (monitoring well B29A0208), in wet years, when base enrichment is already at a sufficient level only small changes in fluxes are shown. In normal years, seepage increases. Also, this is beneficial for the vegetation type.

Watervision
As mentioned in the Materials and Methods-section, WaterVision is used to zoom out and give a broader picture of the impact of climate change on the vegetation types with respect to GLG, GVG, transpiration stress and oxygen stress. All maps can be found in Appendix 6.

First of all, *Blauwgrasland.* The pattern shown in Table 8 is quite representative for *Blauwgrasland* with respect to GLG. The GLG is more suitable for *Blauwgrasland* in Stroothuizen than in Punthuizen. However, GLG in Punthuizen improved when including the measures, but a part of this effect is neutralized by climate change again. Also, *blauwgrasland* is vulnerable to transpiration stress, which results in low transpiration stress target realization for the whole area.

The general pattern is optimistic with respect to GVG, since the optimal groundwater level is reached in a large part of the habitat. On the other side, measures lead to higher GVGs, resulting in more oxygenstress. The oxygen stress maps show an improvement when including climate change due to the small decrease in GVGs.

The situation becomes more optimal for *vochtige heide* when including the measures, but again a part of the effect is neutralized by climate change. However, only small changes are visible when comparing the baseline conditions with the long-term measures & climate change. The measures bring just enough improvement to cope with climate change with respect to GLG. When looking into transpiration stress, we see that low groundwater levels are not a big problem in summer for *vochtige heide*.

With respect to GVG, Table 8 displayed optimal values for GVG in both Punthuizen and Stroothuizen but according to WaterVision, the GVG is in large parts of the area too low. However, *doelgaten* become smaller due to climate change. The target realization for oxygen stress is somewhat better since larger parts reach the target realization of 80 to 100%.

The GLG maps for *zwakgebufferde vennen* show that GLG is only optimal in a small part of Stroothuizen and *doelgaten* increase when including climate change. However, transpiration stress shows high target realizations. This means that periods of low groundwater levels are not too long in most parts and that *zwakgebufferde vennen* are able to cope with these periods of drought.

In all parts the GVG is too low despite measures. This is also visible in Table 8. However, oxygen stress maps show that target realization in the western parts of Stroothuizen I still high. However, GVG and GLG-*doelgaten* are quite large for the Oostven (eastern part and target realization of oxygenstress is also low. But when looking in more detail, the oxygen stress-map

does not have values in the Oostven. This part of Stroothuizen is more vulnerable than the other parts.

For *pioniersvegetaties met Snavelbiezen,* GLG is not taken into account. Only small changes are visible with respect to GVG-*doelgaten*. Climate change has little impact on the *doelgaten* for *pioniersvegetaties* according to WaterVision. The measures bring changes, but climate change does not. Oxygen stress becomes somewhat better in Stroothuizen due to climate change, but differences are quite small. Where the target realization is low, oxygen stress values are quite low (0-10 g O2/m2/10d). Values of 20-30 g O2/m2/10d are found where target realization is high. *Pioniersvegetaties* thus need more oxygen stress in some areas (by higher GVGs).

Finally, *droge heide*. Again GLG is not taken into account since it can cope with quite deep groundwater levels. However, transpiration stress is not optimal for the whole area. Transpiration stress is optimal near the German border, on higher sand ridges, but on the more low-laying parts it's lower. Appendix 7 displays transpiration-stress maps. The areas with higher transpiration stress values, are optimal for *droge heide*. Transpiration stress is too low in the other parts, this means that *droge heide* needs more transpiration stress in some areas.

With respect to GVG, the *doelgat* is 0 everywhere. As mentioned above, GVGs should not be higher than 50cm below surface. When looking into more detail, GVGs are too high in some parts of Punthuizen-Stroothuizen. These parts cope with oxygen stress in winter and therefore have a low target realization for oxygen stress. This is also visible when comparing the oxygen stress-map with the target realization for oxygen stress.

5.6 Synthesis

The current situation in Punthuizen-Stroothuizen is critical, since groundwater levels are too low, periods of inundation too short and fluxes too low. Climate change results in lower GLGs and GVGs, shorter periods of inundation but somewhat higher fluxes. Climate change does puts the achievability of the vegetation objectives even more at risk.

Proposed measures bring relieve, since they increase groundwater levels, fluxes and inundation times.

However, the baseline conditions (or current situation) are suboptimal (Figure 17). Measures were designed to bring optimal conditions to the plants. However, due to climate change these optimal conditions are still not reached and more measures are needed.

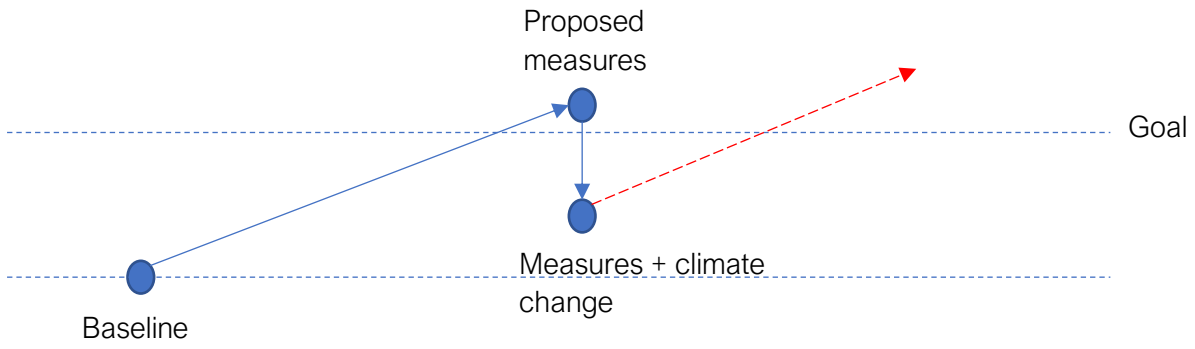

Figure 17: Depiction of realization versus optimal hydrological conditions

6. Discussion

In this study, an available hydrological model was used to research the impact of the proposed measures and climate change on groundwater levels and fluxes and formed the basis of this research. The translation to impact on flora in Punthuizen-Stroothuizen was done by extracting point-data from the model and using WaterVision to calculate GXG-doelgaten and translation- and oxygenstress for the whole area.

6.1 Model results

The model expects only small changes in groundwater levels in winter (-5 to +5 cm) due to climate change. In summer, groundwater levels decrease up to 20 cm. Capel, et al., (2011) expect larger decreases for both winter and summer groundwater levels in the area in which Punthuizen-Stroothuizen is located for the most extreme climate scenario. In sand-areas (like Punthuizen-Stroothuizen), the increase in winter precipitation is not enough to compensate for the lower groundwater levels in summer (Capel, et al., 2011). This is a new insight that is plausible for the research area. With respect to lower GLGs, Capel, et al., (2011) also finds the explanation in decreasing summer precipitation and increased evaporation, just like in this research. The difference in calculated groundwater levels may be caused by a difference in model calibration. Capel, et al., (2011) uses the 'Nationaal Hydrologisch Instrumentarium' (NHI), the model was still under construction and uses large grids of 250x250 m. In our model, the focus is on local dynamics, which are difficult to incorporate in the large grids of the NHI. This may explain the difference in decrease-values in the two models. Gooijer, et al., (2012) also modelled the effect of climate change on grondwater levels in the eastern part of the Netherlands. Changes are of the same order of magnitude as in this research for GLG (0.1 – 0.25 m decrease). For GVG, this is 0.01 to 0.1 m which is also found in this research. Therefore, the model results seem plausible.

However, there are some important sidenotes to make with respect to the model. Model results do not always fit real measurements, since real world groundwater levels are subject to more variables than can be incorporated in the model. The states of the variables that are not included in the model are thus unobserved and not taken into account. This uncertainty leads to the existance of residuals[16]. Bor (2018) made the original model and calculated the residuals of each monitoring well in Punthuizen-Stroothuizen (Appendix 8). With respect to GHG-values, 5 of the 7 used monitoring wells have residuals of -5 to +5 cm. Here, the difference between measurements and model results is thus as small as possible. For the two other monitoring wells, the residuals are bigger (10 to 20 cm). The largest difference between GLG-model-results and measurements are found in Stroothuizen. Bor (2018) finds a possible cause in deviations of reality in the shallow and/or deep soil structure. However, it is difficult to change the soil structure in the model due to the lack of borehole samplings (Bor, 2018). Bor (2018) concludes that the groundwater model is of sufficient quality to be used for effect calculations since the system functioning of the area is properly simulated. The model was not used in the interest of forecasting groundater levels but rather to draw conclusions on the effects of cliamte change and the proposed measures. Assuming the model is not substantially biased with respect to any of the variables that were used, these effect calculations can be considered our best estimates of the real effects and the conclusions that are drawn, based on these estimates, can be considered valid even under model uncertainty.

Thus, the model is suitable for generating GXG-patterns, seasonal patterns and in/decrease values due to measures and climate change. However, it is undesirable to look into specific GXG-values produced by the model, due to the residuals. That is why the *doelgat* calculations, displayed in Table 8, are based on more recent baseline groundwater levels of

[16] Difference between measurements and model results; model uncertainty.

Dongen, et al., (2017), displayed in Table 5. However, *doelgat* calculations by WaterVision are directly based on model values, more information will be given in the next paragraph.

On top of the model-uncertainty, uncertainty is present in the used climate scenario. First of all, in between weather stations, values of precipitation and evaporation are interpolated to come to historical grids. 'The maps are therefore an approximation of the real patterns' (Sluiter, 2014). On top of that, the historical reference dataset is transformed to future time series using monthly change factors (KNMI, 2015a). Both the historical grids and transformed grids have a size of 1 by 1 km. This results in decreasing detail and accuracy, especially when taking into account the relatively small size of Punthuizen-Stroothuizen.

6.2 Impact of climate change on flora

Climate change brings lower groundwater levels in spring and summer, less inundation but higher seepage fluxes. Overall, hydrological circumstances become (more) suboptimal for vegetation due to climate change. The positive part is that the proposed measures neutralize a part of the climate change effect and bring higher fluxes and longer inundation periods. However, more is needed since the current situation is suboptimal.

According to Witte, Runhaar & van Ek (2009), groundwater independent habitat types on higher sandy soils have to deal with larger moisture deficits in growing season due to climate change. This is a logical consequence of dropping GVGs and GLG, and *doelgaten* display similar results but this does not clearly follow from the difference between scenarios with and without climate change in the transpiration maps of Appendix 7. However, WaterVision translates GLG in combination with soil type to drought stress using meta-relations. Drought stress is then translated to transpiration stress per cell. Transpiration stress maps for the whole area (Appendix 7) do not differ that much between scenarios, and therefore, the target realization for the vegetation types stays also roughly the same. So apparently, the in- and decrease in GLGs due to climate change and measures does not clearly lead to more or less transpiration stress. This may be explained by soil type characteristics like capillary rise that is still possible through which water is in reach of the plants. Also, for transpiration and oxygenstress, it is unknown what values are optimal according to WaterVision, thus we cannot check whether those values are logical.
Other aspects sidenotes about the results produced by WaterVision are:

- The soil map used in WaterVision may differ from reality. A different soil type may result in totally different *knikpunten* in WaterVision, However, there has been partly corrected for this effect by changing the *knikpunten* in WaterVision to the more suitable values of Table 4.
- No corrections were made for the model residuals in WaterVision. So for some areas, groundwater levels that are too high or too low are used for *doelgat* calculations.

The effect of climate change on fluxes is supported by literature. Ek, et al. (2007), expects, next to higher groundwater levels due to increased precipitation, also more groundwater recharge and higher seepage fluxes. Witte, Runhaar & van Ek (2009) suggest higher fluxes, but find the explanation somewhere else. The authors argue that soil in infiltration areas dry out in summer, resulting in greatly reduced evaporation which results in higher groundwater replenishment. In this research, this can only be the case when looking at the baseline conditions in combination with climate change. For the other scenarios, groundwater levels increase due to measures, resulting in a higher groundwater level instead of dryer circumstances.

With respect to inundation, this is a result of high groundwater levels in the surrounding areas, so it is entirely dependent on local elevation and drainage aspects. As far as I know, no studies have been conducted that look at the impact of climate change on the duration of inundation.

This research is focussed on the relation between groundwater levels and vegetation. Only changes in groundwater levels are taken into account to look into whether circumstances for the chosen vegetation types stay/become (sub)optimal. With climate change, other factors like groundwater temperature, atmospheric CO2 concentrations, acidification (pH) and soil nutrient status may change. When those aspects change, areas may become suboptimal for the current species, but optimal for other species. This research only focusses on a small part of the impact of climate change.

6.3 Reliability of results, theoretical insights and future research

Based on the information given above, we conclude that this research and the results with respect to the impact of climate change on groundwater levels is reliable enough to answer the research question. This is based on the fact that the model is only used for effect calculations and no value is given to groundwater levels produced by the model.

For the second part, the impact on flora, this is more difficult. Climate change results in lower groundwater levels in summer, shorter inundation periods but higher fluxes. With two negative effects versus one positive effect on top of signs of desiccation and acidification in the area, it would be most likely that circumstances for vegetation types would become more critical due to climate change. Keeping in mind these aspects, the achievability of vegetation objectives would decrease. However, it is difficult to say for which vegetation types the impact will be larger. Point data from the model can be seen as reliable, so for those specific points something can be said about the achievability of vegetation objectives. However, the results of WaterVision are debatable due to the residuals of the model.

This is also the first recommendation for future research. Residuals may be filtered out the output of the groundwater model, which can be used to run WaterVision again. This may give additional insights when combined with this work. On top of that, this research focusses on the impact of hydrological changes, due to climate change, on flora. However, other aspects of climate change should be taken into account to really model the effect of climate change on vegetation, like for example changes in nutrient availability and pH and temperature of groundwater and soil. It is not clear what effects of extreme events are, like long droughts, which are likely to happen more often in the future. Finally, the resilience of habitat types is not taken into account.

Research has been done on the effect of climate change on groundwater levels in urban areas, land subsidence, drinking water sector, water quality, surface water, recreation and tourism in the Netherlands. However, theoretical insights are broadened by this research since more knowledge about the impact of climate change on the hydrological system is gained. A more detailed picture is drawn of the impact of climate change Natura 2000 area of Punthuizen-Stroothuizen and which effects are positive and which negative. Similar, detailed studies like this are scarce. Also, knowledge about the effects in combination with measures may help other areas to be aware of how much impact measures should have to cope with climate change. On top of this, effect calculations are also important for the agricultural areas surrounding Punthuizen-Stroothuizen which also have to cope with dryer circumstances in summer.

In the future, we should make sure measures are added to the long-term measures to guarantee summer groundwater levels are sufficiently high for the vegetation types. Second, we should create awareness at the surrounding agricultural enterprises with respect to the effects of climate change. Finally, more research is needed to get a broader picture of the effects of climate change on flora.

7. Conclusion

Six sub questions are answered throughout this report. The current groundwater levels fluctuate throughout the year. In winter, parts of Punthuizen-Stroothuizen are inundated, while in eolian sand ridges groundwater level is still quite deep. In summer, groundwater levels drop quite deep, especially in the eolian sand ridges. Desiccation is a problem in the area, resulting in two measurement sets to increase groundwater levels: short-term and long-term measures. The short-term measures lead to maximal 30 cm higher groundwater levels in winter in the area of Punthuizen-Stroothuizen. In summer this is 20 cm. With respect to long-term measures this is more in Punthuizen than in Stroothuizen. In Stroothuizen, the effects are still maximal 30 cm in winter and 20 cm in summer. In Punthuizen, groundwater levels increase up to 40 cm in both winter and summer.

The effects of climate change are less visible in winter than in summer. In winter only small changes (-5 to +5 cm) are visible, while in summer the groundwater levels drop up to 20 cm. In summer, measures are thus almost neutralized by climate change. However, climate change brings an increase in fluxes, which is a positive effect.

The current situation is not optimal for flora. Groundwater levels are too low, especially in Punthuizen. On top of that, base enrichment seepage is too low and periods of inundation are too short to be optimal for the chosen habitat types. The effects of climate change result in even lower groundwater levels and shorter periods of inundation. The only positive effect is higher fluxes, but this is not enough to compensate for the other effects. Achievability of vegetation objectives is thus jeopardized even more by climate change. However, the measures bring positive effects. Groundwater levels increase, fluxes increase even more and periods of inundation are extended. It thus can be concluded that the measures are more than necessary in the future and even more is needed to make sure summer groundwater levels are also increasing in Stroothuizen under a changing climate.

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9. Appendices

Appendix 1: Model description and input data

The model made by TAUW is divided in two parts. The unsaturated zone is modelled by MetaSWAP and is used to simulate "the process of groundwater recharge and discharge through the unsaturated zone" and interactions between soil, vegetation and atmosphere (Vermeulen, et al., 2017). MODFLOW is used to model the saturated zone. Both models include the processes of groundwater recharge and capillary rise (Gurp, 2016). However, MODFLOW simulates both horizontal and vertical groundwater flow in the saturated zone and MetaSWAP only simulates the vertical direction but is divided into multiple parallel, vertical columns. MetaSWAP thus assumes "that unsaterated flow takes place within parallel, vertical columns, with each column connecting to a simulation unit of a groundwater model" (Walsum & Groenendijk, 2008).

1. MetaSWAP

According to Walsum & Groenendijk (2008), MetaSWAP covers the Soil-Vegetation-Atmosphere-Transfer (SVAT) interactions (Van Walsum, 2010). MetaSWAP requires a high number of input parameters to simulate interactions in the unsaturated zone (Input data). Meteorological data (precipitation and evaporation) is the only input that "should be available in the form of a step-function with a time interval of t_s" (Walsum, Veldhuizen, & Groenendijk, 2011).

Precipitation

The total (gross) precipitation consists of natural precipitation and sprinkling. In the model of TAUW, only daily natural precipitation is included. In MetaSWAP, precipitation can either fall directly on the surface (free throughfall) or it can be stored at the vegetation canopy (interception). Interception subsequently can evaporate from the canopy or it can reach the surface as stemflow or drops from the leaves. The evaporation rate of the canopy storage depends on the degree of canopy saturation. Also, the canopy storage is linked to the leaf area and thus dependent on the season and vegetation type. When the canopy storage is saturated, dripping starts and "all excess precipitation becomes throughfall".

Crop and evaporation characteristics are fed to the model using the land-use (LUSE_SVAT) and vegetation factors and interception characteristic (FACT_SVAT) inputfiles (Walsum, 2010).

Evaporation

Potential evaporation is the amount of water that evaporates with optimal water availability. In regional models, the potential evaporation can be computed in two ways:

- Using a reference crop evapotranspiration
- Involving a physical description of the evapotranspiration processes.

When looking into the reference crop evapotranspiration method, two different options are available: the Penman-Monteith transpiration for short grass and the Makkink reference crop evapotranspiration. The last one is used in the model for Punthuizen-Stroothuizen and "for the Makkink method only the values of the reference evapotranspiration (ET_{Mak}) are needed" (Walsum, Veldhuizen, & Groenendijk, 2011). To calculate ET_{Mak} for a particular day, only the incoming shortwave radiation and mean daily temperature are needed (Hiemstra & Sluiter, 2011). Incoming radiation and temperature at KNMI monitoring stations, reference evapotranspiration is calculated, interpolated and transferred to grids.

Potential evapotranspiration is divided into four different types: evaporation from a wet canopy (interception evaporation), dry canopy (transpiration), wet, bare soil (bare soil evaporation) and ponded soil (ponding evaporation). Evapotranspiration rates for those four is calculated by multiplying the reference crop evapotranspiration rate (ET_{Mak}) by the crop factor. The crop factor

depends on the crop and on the type of evapotranspiration. In MetaSWAP is assumed that when "interception evaporation is active, the other processes (canopy transpiration, ponding evaporation and soil evaporation) are considered to be inactive".

From potential evapotranspiration, we have to move to actual evapotranspiration. When looking at actual transpiration, MetaSWAP uses the following relationship (Walsum, Veldhuizen, & Groenendijk, 2011):

$$T_a = T_p * \alpha_E$$

Where:

T_a = actual evaporation rate (m d^{-1})
T_p = potential canopy transpiration rate (m d^{-1})
α_E = soil moisture reduction factor (-)

The soil moisture reduction factor α_E thus influences the actual evaporation rate. When $\alpha_E = 1$, the evaporation is at its maximum 'potential'. When the soil water pressure head decreases, α_E becomes at a certain moment slightly smaller than 1, this is the reduction point. When the soil water pressure head keeps decreasing, the wilting point is reached when the water uptake by the roots is zero ($\alpha_E = 0$). Between the wilting point and the reduction point, α_E reduces from 1 to 0 and therefore also the actual evaporation rate reduces linearly. On the other hand, when the soil water pressure head is too high, oxygen deficiency in the root zone results in reduced water uptake. Again, α_E will reduce from 1 to 0 with high soil water pressure heads.

Actual ponding evaporation is reduced by the activity of other evapotranspiration terms or by the reduced availability of ponding water (Walsum, Veldhuizen, & Groenendijk, 2011). As mentioned earlier, interception and transpiration have priority over ponding and soil evaporation. Thus:

$$E_{pond} = \min\left\{E_{p0} \cdot (1-W_{frac}) \cdot (1-T_{frac}) \; ; \; S''_{pond} / \Delta t_s\right\}$$

Where:

E_{pond} = actual evaporation rate of ponding water (m d^{-1})
E_{p0} = potential evaporation rate of ponded water (m^3 m^{-2} d^{-1})
W_{frac} = time fraction that interception is active (-)
T_{frac} = time fraction that is transpiration active (-)
S''_{pond} = amount of ponding water after update for infiltration

So the lowest of the two parts of the equation becomes the actual evaporation rate of ponding water.

Soil crusting is important for actual evaporation, since the dried out upper soil crust limites moisture loss. This is to complex to model, so the method of Boesten and Stroosnijder (1986) is used to model this. "The bare soil evaporation for a time step is derived from a simple model for the *cumulative* values of actual and potential evaporation since the start of the drying period" (Walsum, Veldhuizen, & Groenendijk, 2011). When the squared empirical soil parameter is equal or larger than the sum of the potential evapotranspiration, the sum of the actual evaporation is equal to the sum of the potential evaporation.

When $\sum E_p \leq \beta_2^2$ then $\sum E_a = \sum E_p$
When $\sum E_p > \beta_2^2$ then $\sum E_a = \beta_2 \sqrt{\sum E_p}$

Where:

B_2 = empirical soil parameter, with a default value of 0.054 ($m^{1/2}$)

$\sum E_a$ = sum of actual evaporation since the start of the drying period (m)
$\sum E_p$ = sum of potential evaporation since the start of the drying period (m)

So, as mentioned earlier, precipitation and Makkink reference evapotranspiration are the only two data types that have to be fed in daily time steps to the model.

Soil water-module

From the Soil-Vegetation-Atmosphere-Transfer module (SVAT), we now move to the soil water-module within MetaSWAP. "The subsurface soil water dynamics are described using two control boxes: for the root zone and the shallow and deep subsoil" (Walsum, Veldhuizen, & Groenendijk, 2011). The root zone is the upper layer of the soil from which plants extract water. Processes that bring changes to the soil moisture content are infiltration, transpiration, capillary rise, percolation and soil evaporation (Gurp, 2016).

To describe processes in the soil layers properly, two parameters are needed:

- Maximum infiltration rate
- The microstorage capacity.

Also, to model unsaturated flow, soil physical metafunctions are needed for:

- The percolation/capillary rise
- Root zone storage
- Subsoil storage

All the water that reaches the surface, can infiltrate. However, it is limited by the maximum infiltration rate and maximum storage. When it cannot infiltrate, it is stored on the soil surface in micro- and macro-storage. Micro storage takes place in the soil surface at sub-grid scale. "The water in macro-storage can freely move over the soil surface" (Walsum, Veldhuizen, & Groenendijk, 2011). However, overland flow is modelled by the MODFLOW overland flow package instead of MetaSWAP. Ponded water (macro-storage) can evaporate.

Infiltration and ponding are coupled in MetaSWAP. At the start of a specific time step, "groundwater present above soil surface is converted into ponding water" (Walsum, Veldhuizen, & Groenendijk, 2011). Infiltration can only happen when water is ponded from the last period or in case of net precipitation. The infiltration has priority over evaporation from ponding water. The maximum available infiltration rate from ponding water is then calculated and it is checked whether saturated conditions are present. Infiltration takes place only when the groundwater head is lower than that of the ponding water.

The maximum amount of storage available for infiltration is now calculated using the root zones saturated water content, water content at the beginning of the time step, soil evaporation, infiltration and transpiration of the last time step, the percolation rate and the maximum infiltration rate.

Now the amount of water stored in the ponding reservoir is updated and determines how much water is left for evaporation and runoff. Afterwards, a new time step starts again.

Unsaturated flow

MetaSWAP assumes that unsaturated flow only takes place in parallel vertical columns. The groundwater level moves up and down and forms the 'moving boundary' between the soil columns and the groundwater model. Solutions to Richards' equation are used as building blocks to model unsaturated flow. "The appropriate building blocks are selected on the basis of water balances at the aggregate scale of control volumes for the rootzone and subsoil" (Walsum, Veldhuizen, & Groenendijk, 2011).

The flow equation for one-dimensional flow in an unsaturated soil with root extraction can be written as:

$$\frac{d}{dz}\left[K(v)\left(\frac{dv}{dz}+1\right)\right]-\tau(v,z)=0, \qquad 0 \geq z \geq h$$

Subject to the boundary conditions

$$v(h)=0$$

$$\left[K(v)\left(\frac{dv}{dz}+1\right)\right]_{z=0}=-q(0)$$

Where

z	=	elevation coordinate, taken positively upward (zero at the soil surface) (m)
h	=	groundwater elevation (m)
v	=	pressure head (m)
K(v)	=	hydraulic conductivity as a function of pressure head (m d^{-1})
q(0)	=	flux density at the soil surface, taken positively upward (m d^{-1})
$\tau(v,z)$	=	depth- and head-dependent extraction term for root water uptake ($m^3m^{-3}d^{-1}$)

In pre- and post-processing stages, calculations have been done to keep computational effort as small as possible. During pre-processing, steady states for each soil type and root zone depths are already computed in between boundary conditions of example extreme potential infiltration and evapotranspiration and shallow and deep groundwater elevations. Per computed steady-state profile, the combination of the pressure head (v) and groundwater elevation (h) is unique. A look-up table displays the relationship between root zone storage, pressure head in the root zone and groundwater elevation. Based on this look-up table, the moisture content and groundwater table together can tell what the pressure head of the steady state profile is. This pressure head then is used in another look-up table to find the corresponding capillary rise and percolation for the steady state profile (Gurp, 2016).

2. MODFLOW

Since the unsaturated zone in MetaSWAP is modelled in one dimension (vertical) and the saturated zone in MODFLOW in three dimensions, a coupling has to be made. Two types of links can be used to couple MetaSWAP and MODFLOW:

- i-link (integral), in which the groundwater level of the SVAT-unit in MetaSWAP and the head in MODFLOW are kept equal. The i-link is most commonly used.
- c-link (compartment), where a head difference is involved. The c-link is only used when groundwater heads are above soil surface and information “about the vertical resistance of the soil surface” is available (Walsum, Veldhuizen, & Groenendijk, 2011).

When MetaSWAP and MODFLOW are coupled, regional groundwater flow needs to be calculated by MODFLOW. MODFLOW uses Darcy’s law to model “the flow of a homogeneous incompressible fluid through a porous medium” (Walsum, Veldhuizen, & Groenendijk, 2011). In MODFLOW, the aquifer is divided into a system with a grid of blocks or cells. Rows, columns and layers describe the location of a specific cell (Harbaugh, 2005). The continuity equation is used to calculate groundwater flow and assumes “the sum of all flows into and out of the cell must be equal to the rate of change in storage within the cell” (Harbaugh, 2005). The balance of flow for a cell becomes:

$$\sum Q_i = SS\frac{\Delta h}{\Delta t}\Delta V$$

Where

Q_i	=	a flow rate into the cell (L^3T^{-1})

SS = the specific storage, the volume of water that can be injected per unit volume of aquifer material per unit change in head (L^{-1})
ΔV = the volume of the cell (L^{-3})
Δh = the change in head over a time interval of length Δt

The right-hand term is "equivalent to the volume of water taken into storage over a time interval Δt given a change in head of Δh" (Harbaugh, 2005). Darcy's law is used to calculate the flow into a cell (Q) from the 6 adjacent cells and depends on the head of the cells, hydraulic conductivity, the area of the cell and the distance between the middle of the cells. So in total, to get the flow into the middle block, 6 times Darcy's law is used to calculate the flow from the adjacent cells to the middle cell. To account for flows into the middle cell from other sources like rivers and wells, more terms are added to the continuity equation to correct for this.

Afterwards, the $\Delta h/\Delta t$-term will "be expressed in terms of specific heads and times" (Harbaugh, 2005) and this is done by replacing

$$\frac{\Delta h}{\Delta t} \quad \text{by} \quad \frac{h^m - h^{m-1}}{t^m - t^{m-1}}$$

Where
t^m = the time at which the flow of the continuity equation is evaluated
t^{m-1} = the time precedes t^m
The head values associated with these two times are h^m and h^{m-1} respectively.

The continuity equition is solved per cell and for each time step. The heads at the beginning of the time step are known and the head of the end of the time step has to be obtained by solving the equation.

3. Input data

MetaSWAP needs a lot of input data to include interactions in the unsaturated zone, for example land-use type, rootzone thickness, surface elevation, artificial recharge and urban area. SVAT-files describe relationships and feedbacks, for example interception characteristics of vegetation, parameters for soil evaporation and land-use options and their characteristics but also meteorological data is supplied. Meteorological data contains for example precipitation, evapotranspiration, minimum and maximum day temperature, mean temperature, radiation, humidity and wind speed (Van Walsum, 2010).

After the MetaSWAP inputs, the specifics for each layer are stated. The used model uses a grid cell size of 25 by 25 meters and contains 7 layers, so 7 different types of soil. Specifications have been assigned to each of the layers.
The description of the different parameters used for layer specification are described in Table 9. Also, it gives per parameter the values included in the model. These specifics do not change over time but are fundamental to model water flow.

Table 9: Description of used parameters for layer specification in Punthuizen-Stroothuizen-model and values

Parameter	Description
Boundary conditions	For each layer it consists of a grid that includes per cell whether the cell acts as a fixed boundary condition with a constant head (-1), is excluded from the simulation (=0/NoDataValue) or takes part of the simulation and groundwater flow and head is computed (>0). For this model, all cells are active and included.
Starting head (SHD)	For each model layer it is specified for each cell what is the initial head at the start of the simulation. For all layers, the starting head increases

	from northwest to southeast and differ between approximately 25 and 29 m+MSL[17]. Values do not differ a lot between the different layers.
Transmissivity (KDW)	The transmissivity tells at which rate groundwater flows through an aquifer horizontally (Robinson, 2018). Per cel and per layer, the transmissivity changes in the original model. Unit of KDW is m^2/day. Values of the layers differ: Layer 1: <5 to ±120 Layer 2: ±100 to ±700 Layer 3: ±30 to ±350 Layer 4: <5 to ±80 Layer 5: <5 to ±55 Layer 6: <5 to ±55 Layer 7: <5 to ±40
Vertical Resistance (VCW)	Vertical resistance expresses the resistance to flow when a liquid flows through a porous medium. The vertical resistance between model layers is expressed in days. Layer 1: <1 to ±55 Layer 2: most values between 1 and 10, near border higher values between 30 and 300 Layer 3: eastern part: 1 to 10, increasing to the southwest to values around 10,000 Layer 4: <1 to ±10 Layer 5: all values below 2.4 Layer 6: all values below 2.5
Storage Coefficients (STO)	The storage coefficient is dependent on the lithology of the layer. The storage coefficient or storativity is the amount of water that is expelled from the aquifer if the head in the aquifer declines by one unit (Fitts, 2012). Each model layer has its own storage coefficient. The storage coefficient is 0.15 for the first layer. For all the other layers, it is 0.0007.
Top of aquifers (TOP)	The top of the aquifer is described by a value for the top level of the permeable part of each cell in m+MSL. Values for all layers increase from northwest to southeast. Layer 1: ± 24 to ± 31 Layer 2: ± 23 to ± 31 Layer 3: ± 7 to ± 17 Layer 4: ± -35 to ± 3 Layer 5: ± -35 to ± -4 Layer 6: ± -37 to ± -8 Layer 7: ± -37 to ± -12
Bottom of aquifers (BOT)	The bottom of the aquifer is described as the bottom level of the permeable part of each cell in m+MSL. Values for all layers increase from northwest to southeast and approximate the TOP values of the layer below.
Horizontal anisotropy module	With isotropic conditions, permeability *k* is equal in the x and y direction in the model layer. With anisotropic conditions, permeability *k* is not equal in the x and y direction. This results in flow non perpendicular to the piezometric head (Vermeulen, Burgering, Roelofsen, Minnema, & Varkaik, 2017). Anisotropy is given per cell per layer and anisotropic angle and anisotropic factor of the cell. The anisotropic angle is "the angle along the main principle axis (highest permeability *k*) measured in degrees

[17] Meter above Mean Sea Level/NAP

	from north (0°), east (90°), south (180°) and west (270°)". The anisotropic factor is perpendicular to the main principal axis and is between 0.0 (full anisotropic) and 1.0 (full isotropic) (Vermeulen, Burgering, Roelofsen, Minnema, & Varkaik, 2017). Anistropy is only included in layers 2, 3 and 4. The anisotopic factor is the same per cell for each of the 3 layers and differs between 0.248 and 1. Also the angle does not differ between layers and is either 160 or 0.

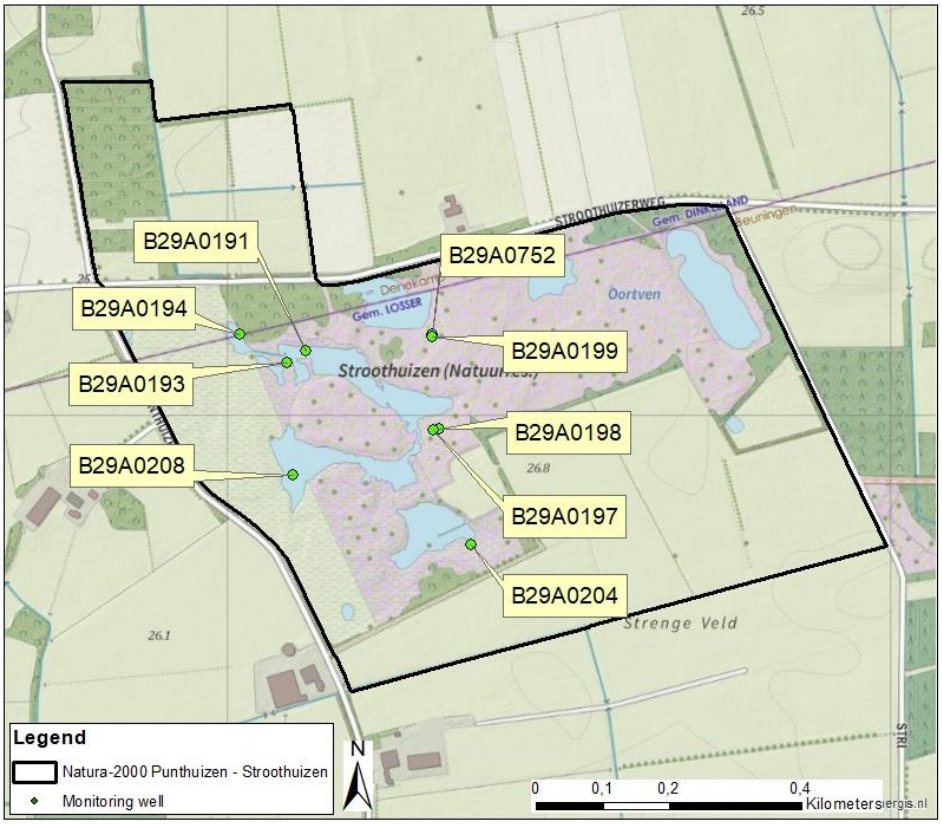
The specification presented in Table 9 do not change over time. Table 10 shows packages that may change over time, like well abstraction or drainage.

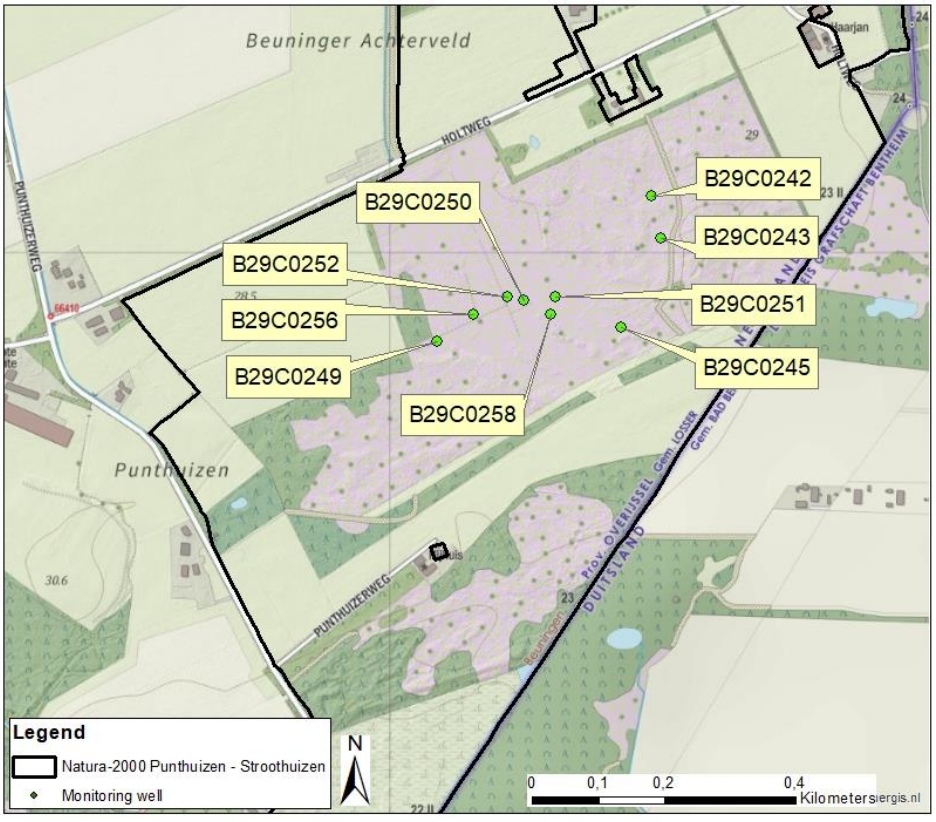
Table 10: Instationairy model packages of Punthuizen-Stroothuizen-model

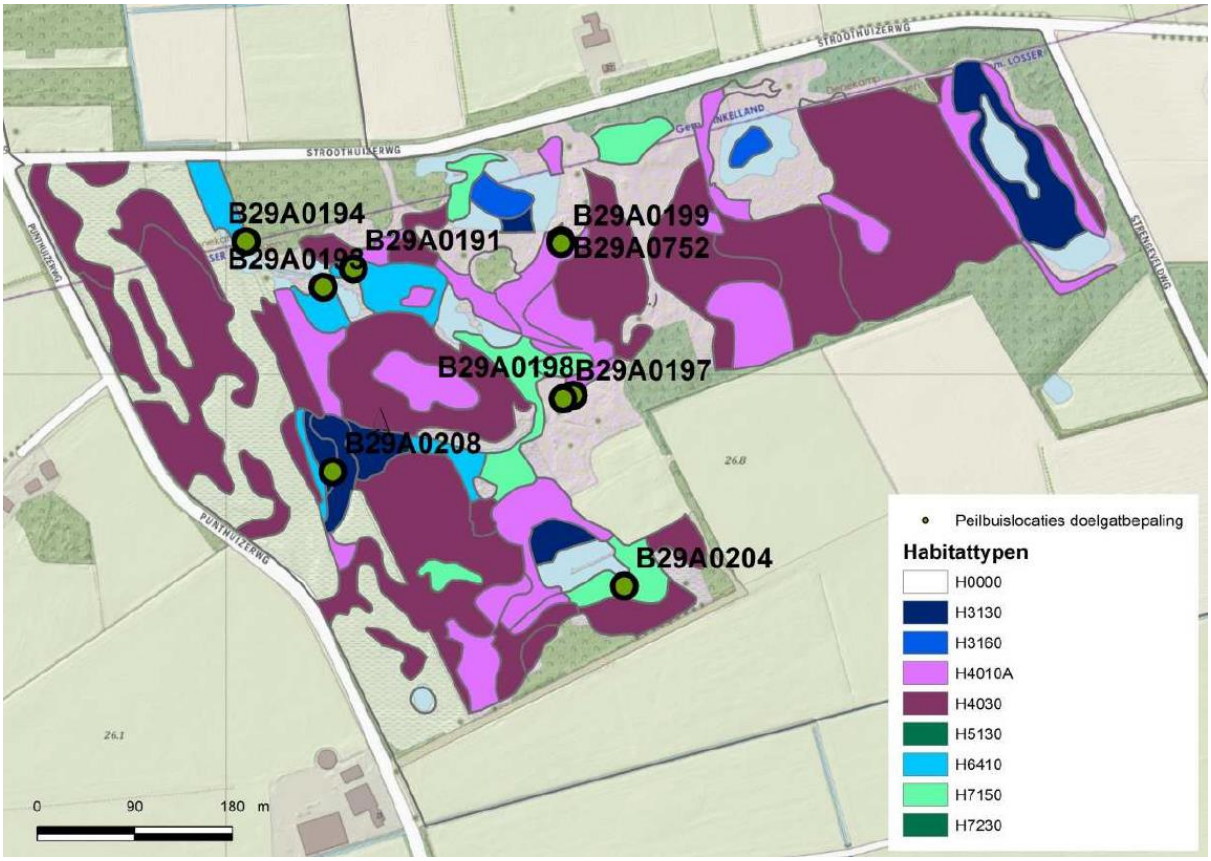
Package	Description
Well abstraction	Per layer is given where well locations can be found based on coordinates. Per well location, an average abstraction or a link to a text-file with abstraction time series is given. This information is translated into a grid for each timestep so that it can be used to model the influence of the abstraction. The Punthuizen-Stroothuizen model includes 4 different types of abstractions: industrial, drinking water, German and 'normal' abstractions. For each of these types, the model gives the abstraction per layer.
Drainage	With this package, "drainage pipes and drainage ditches by which water is removed from the model when the calculated head in a model layer exceeds the elevation of the drainage system" is represented (Vermeulen, et al., 2017). This is based on the elevation and conductance of the drainage system.
River Package	"The river package defines the location, the water level, the bottom level, the conductance and the infiltration factor by four grid files." (Vermeulen, Burgering, Roelofsen, Minnema, & Varkaik, 2017) Rivers, creeks, channels or drainage ditches infiltrate or drain. This package assumes that rivers never dry out. In the Punthuizen-Stroothuizen model, different types of 'rivers' are distinguished. First of all large leggerwatergangen[18]. These can drain or infiltrate. Second and third are channels and drainage ditches, respectively. Per type water level, bottom level and infiltration factor is given. At the 1st of May and at the 1st of October of each year, water level, conductance and bottom level are changed from summer to winter values or the other way around.
Overland flow	Overland flow happens when the groundwater head becomes higher than the surface elevation. In this package, the elevation is defined when overland flow occurs. Overland flow itself is not modelled. When the groundwater head becomes larger than the threshold value, water is discharged out of the model and does not return to groundwater. Water thus 'disappears'.

[18] Large channels/rivers managed by water boards.

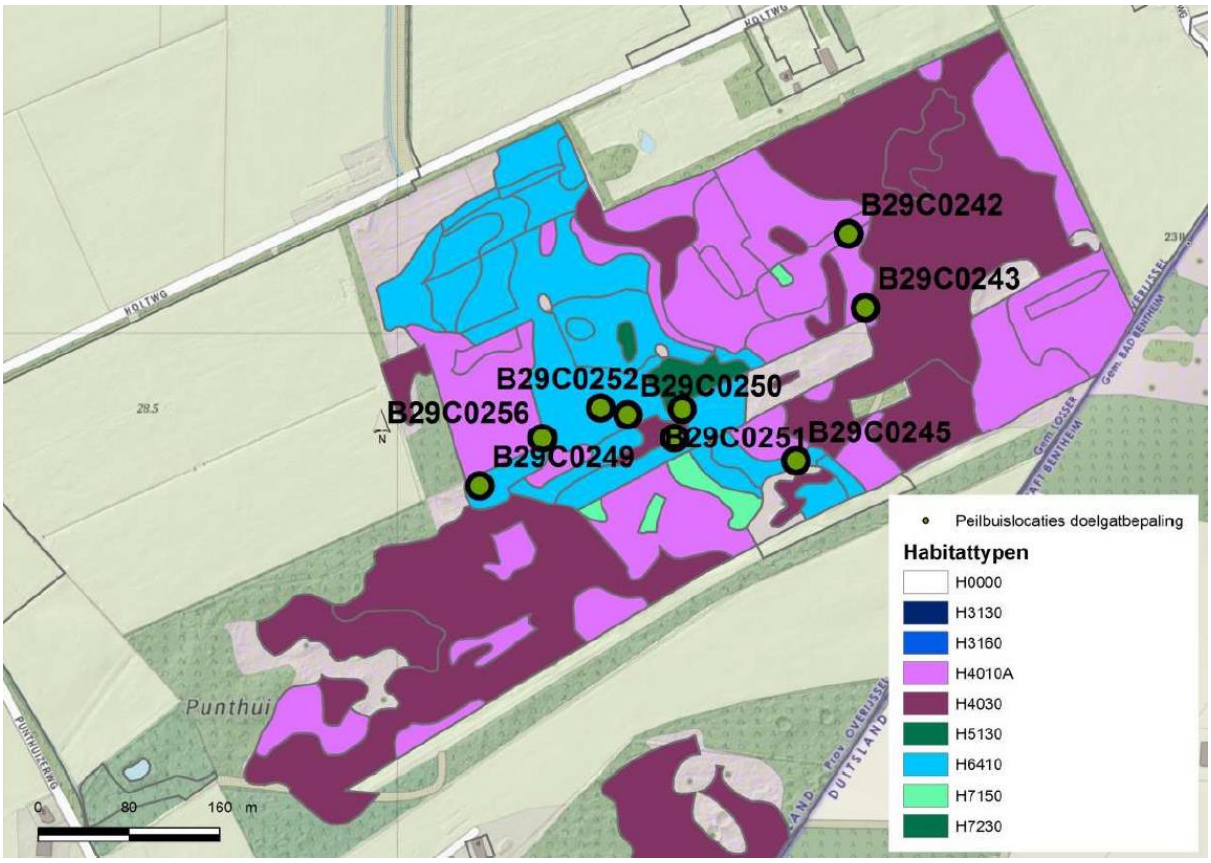
Appendix 2: Monitoring wells of Punthuizen & Stroothuizen







Dongen, Eysink, Ent, & Brummelman, 2017

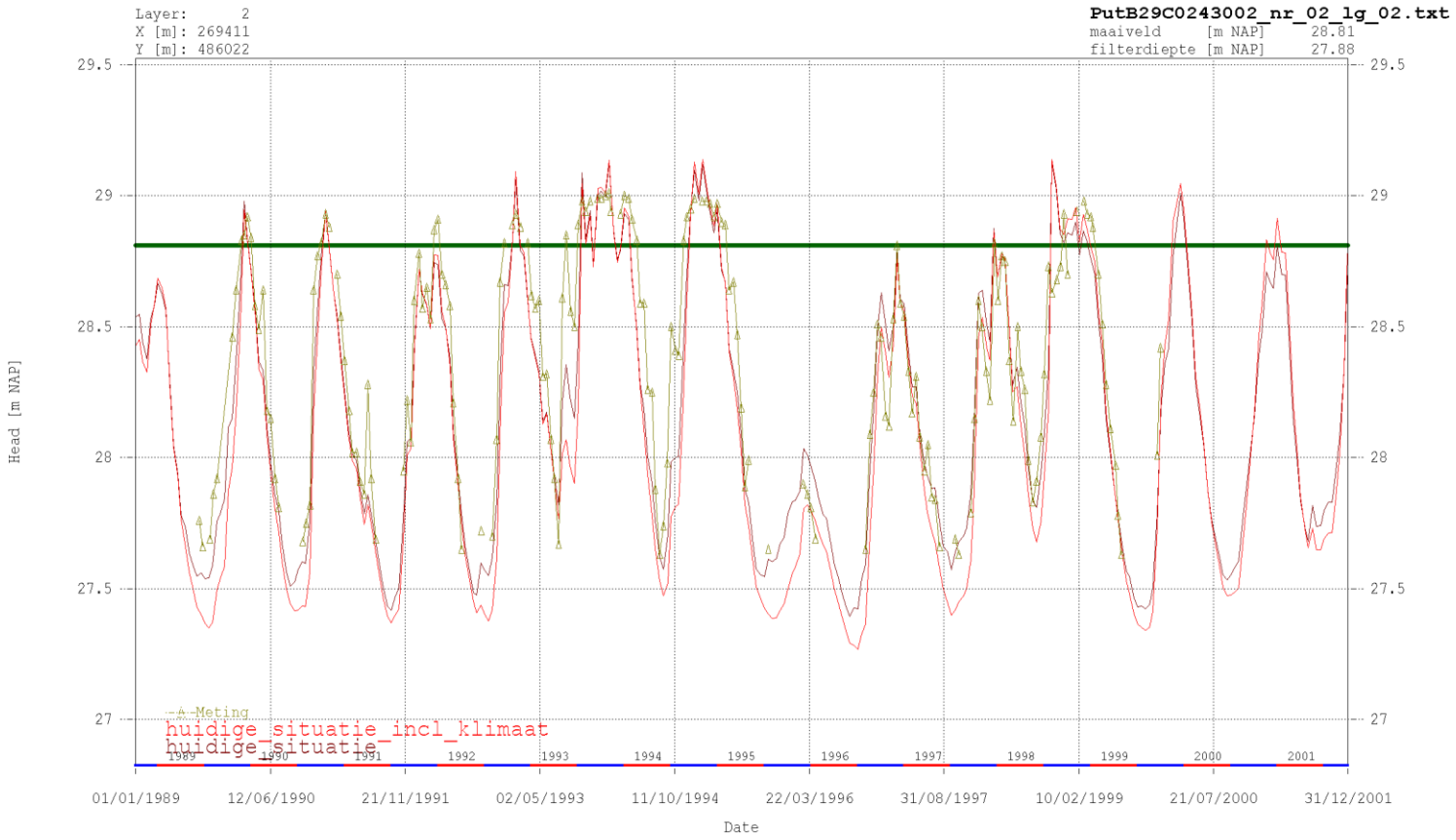


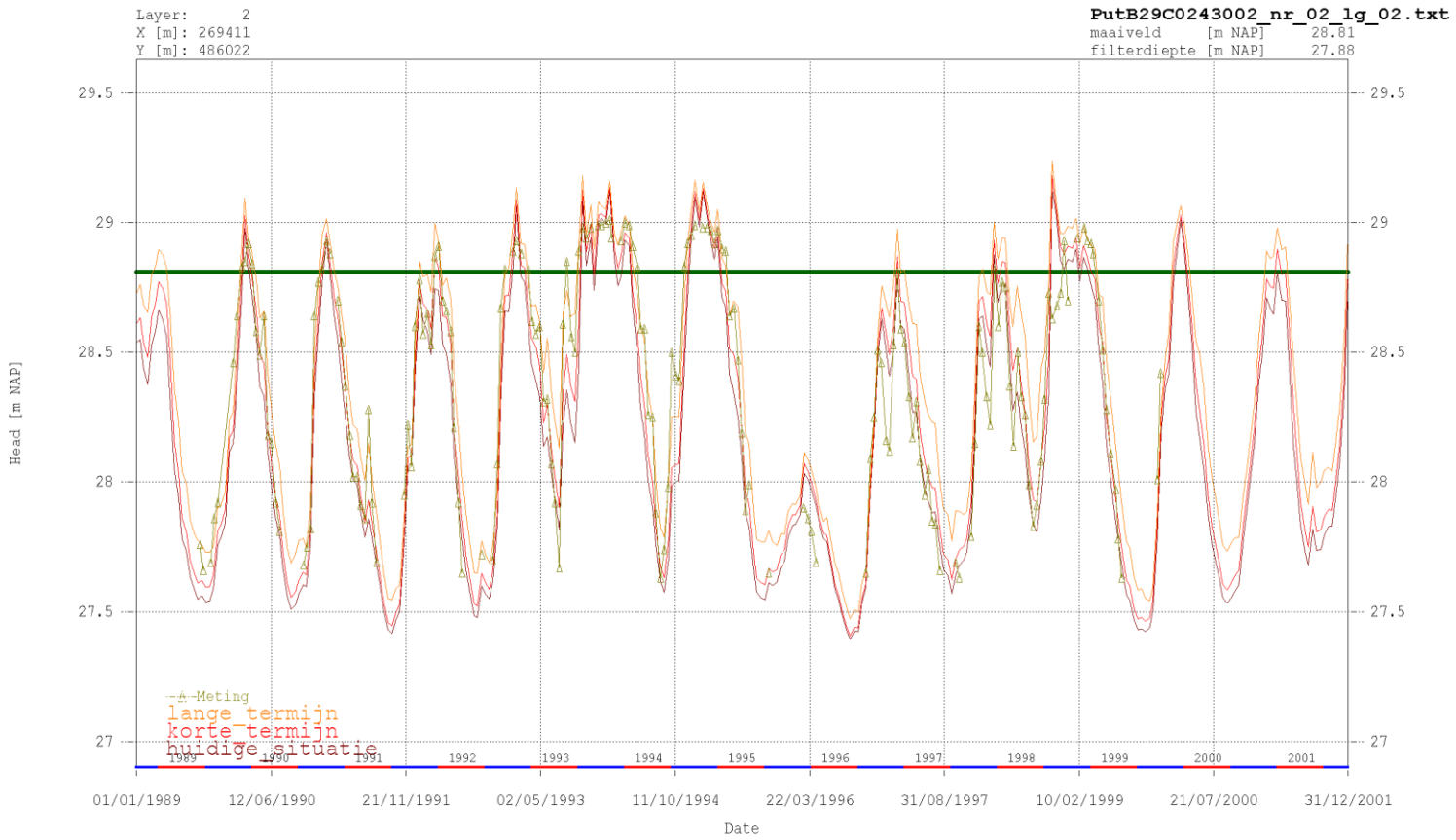
Dongen, Eysink, Ent, & Brummelman, 2017

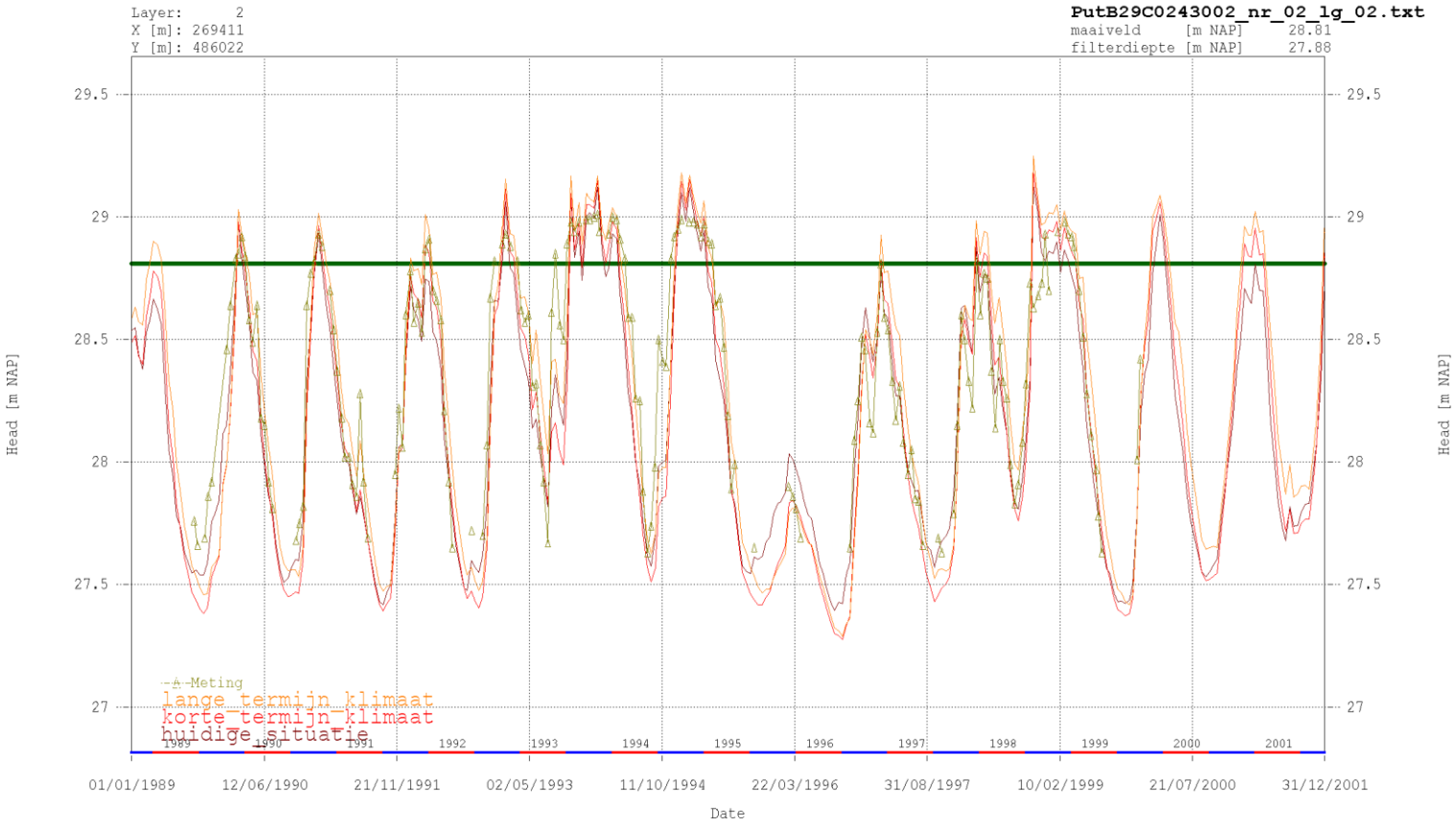
Appendix 3: Time-hydraulic-head-lines

Punthuizen

B29C0243



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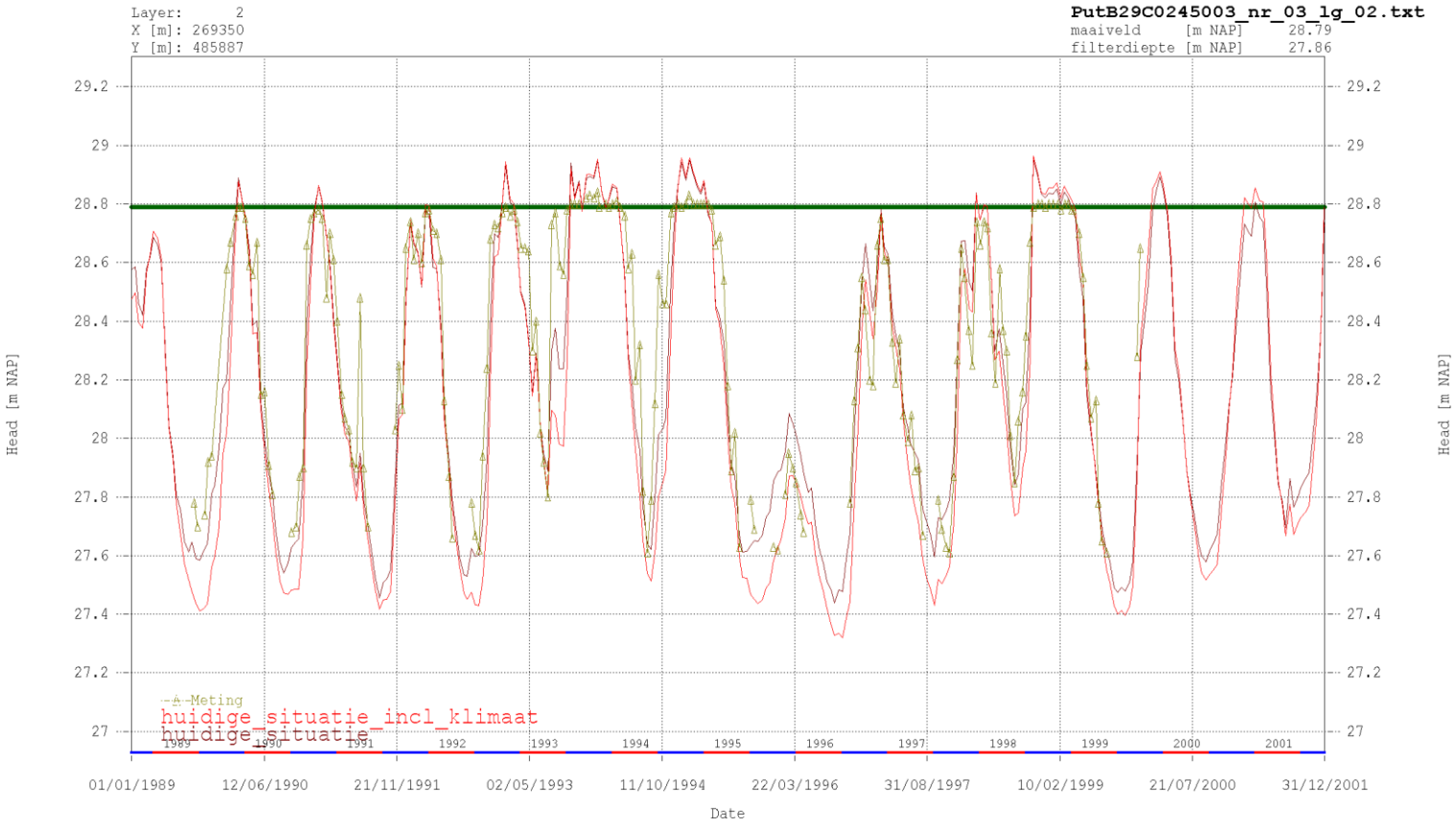
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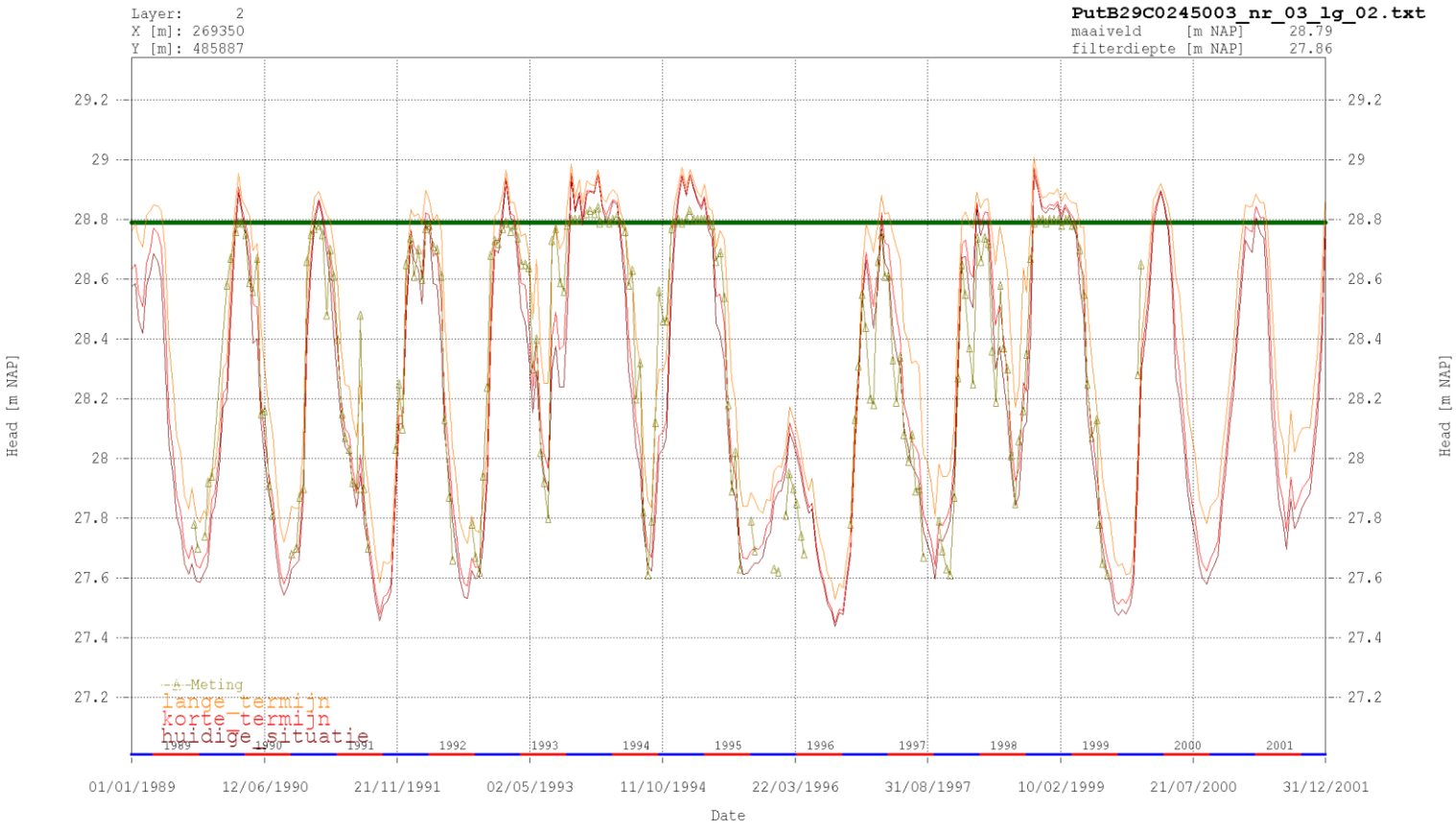
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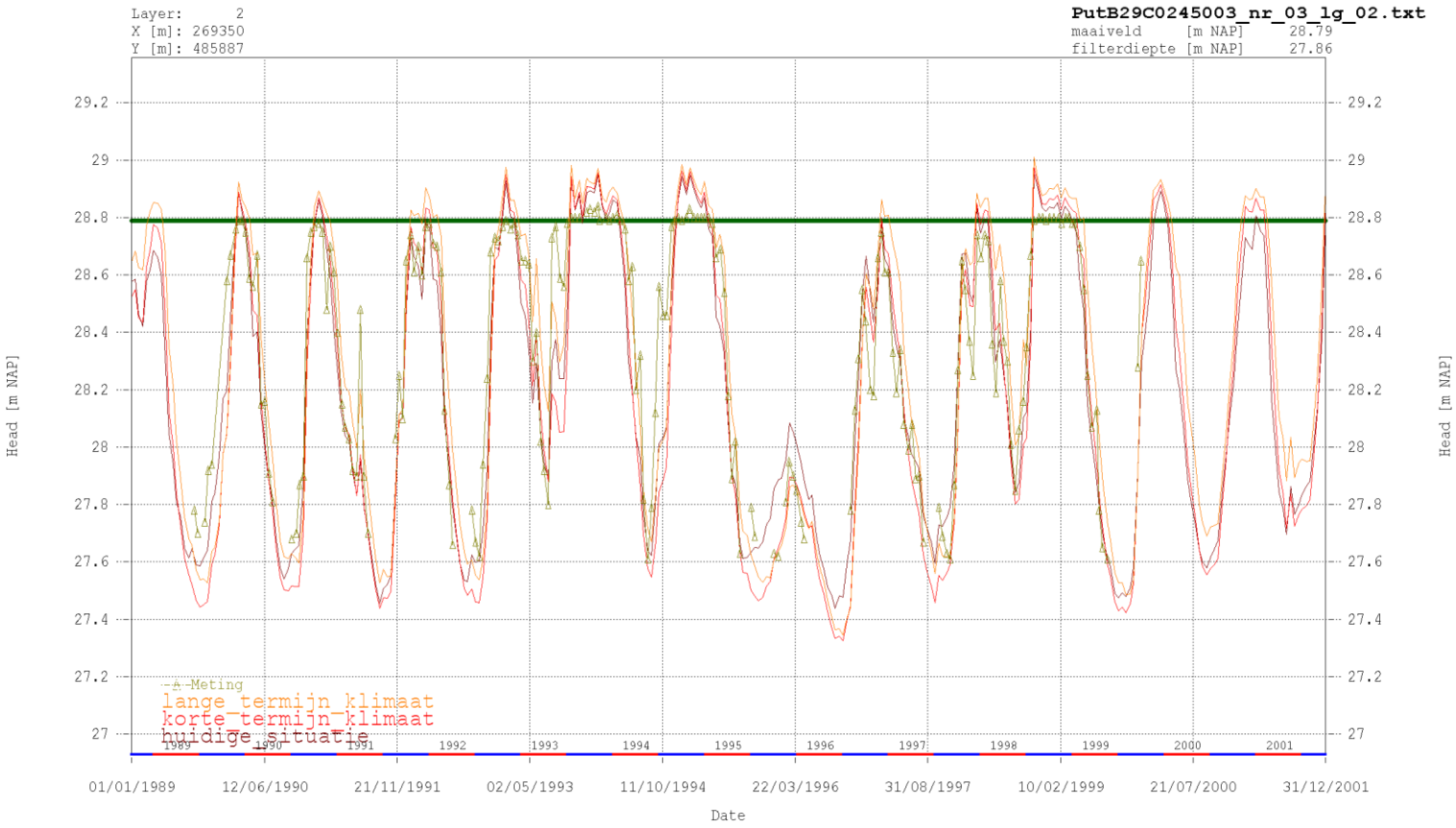
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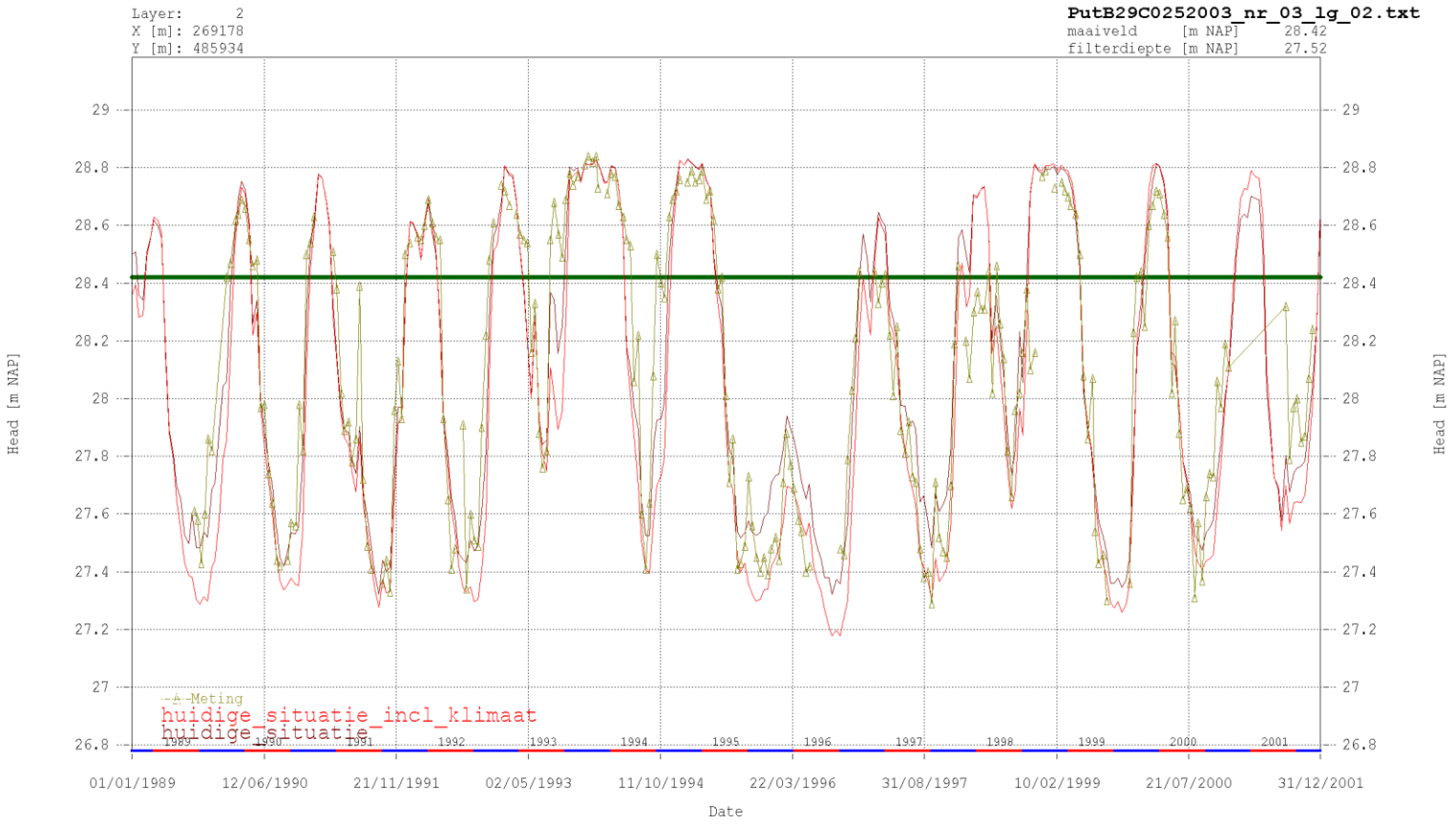
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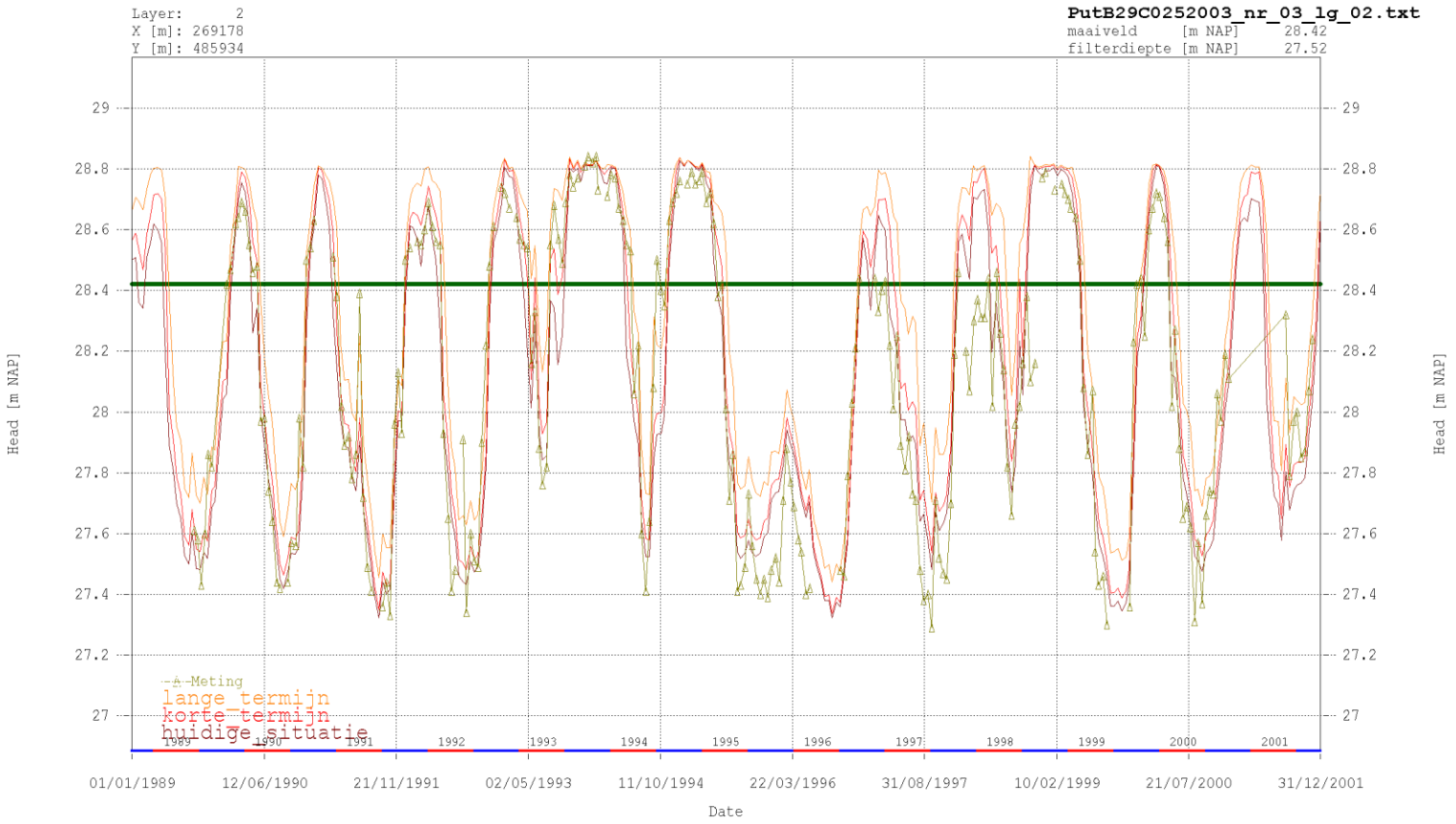
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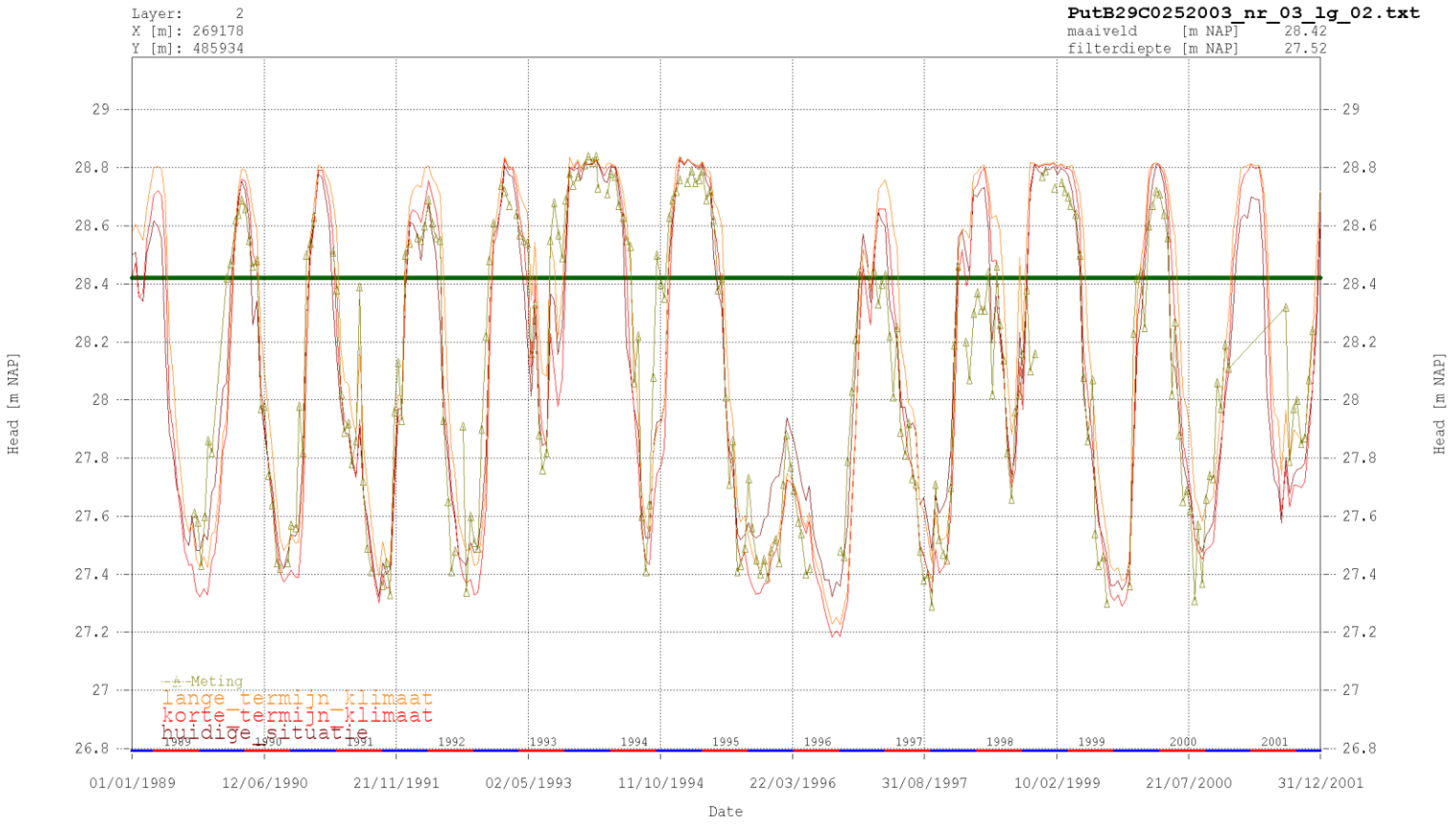

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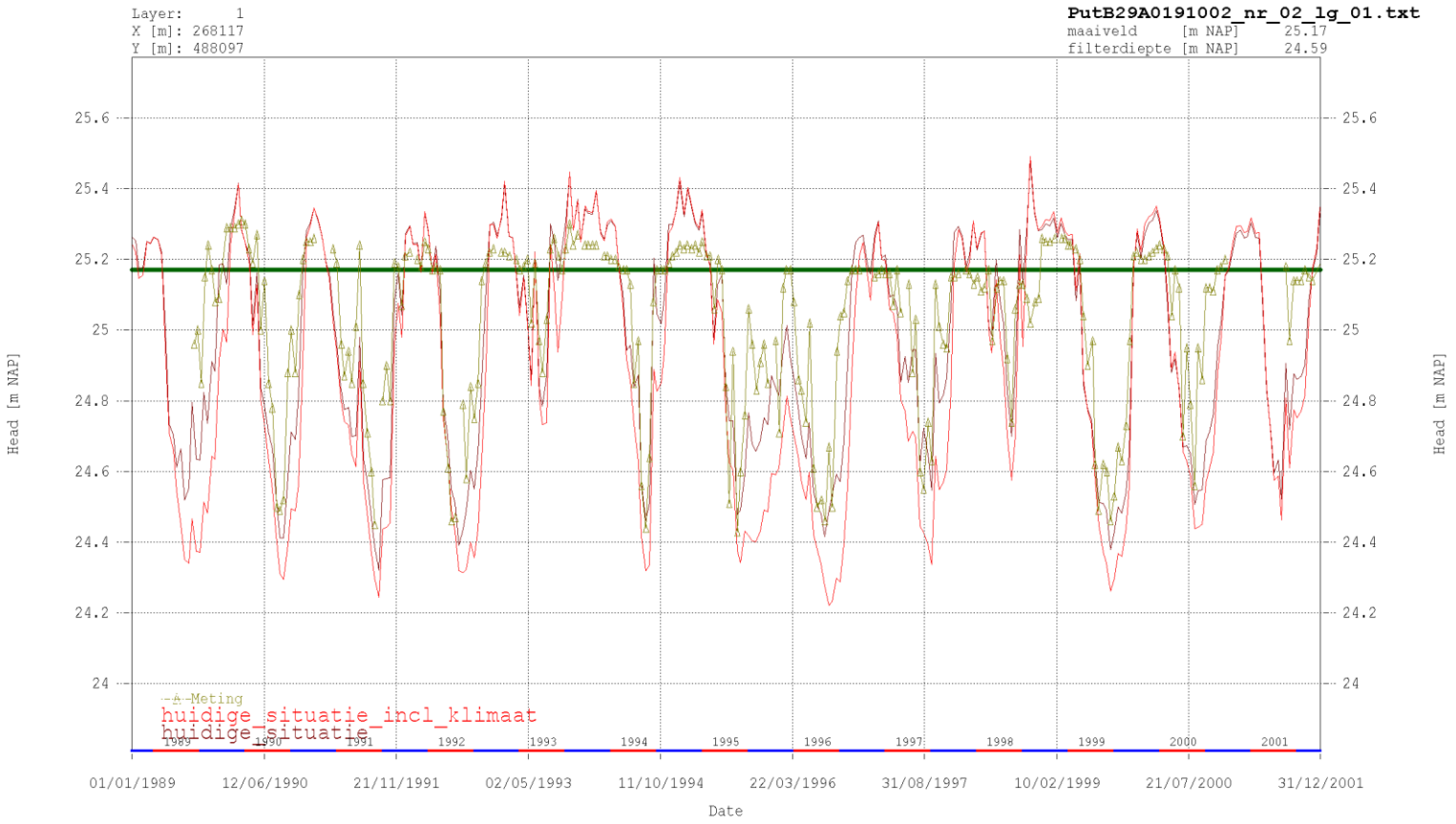

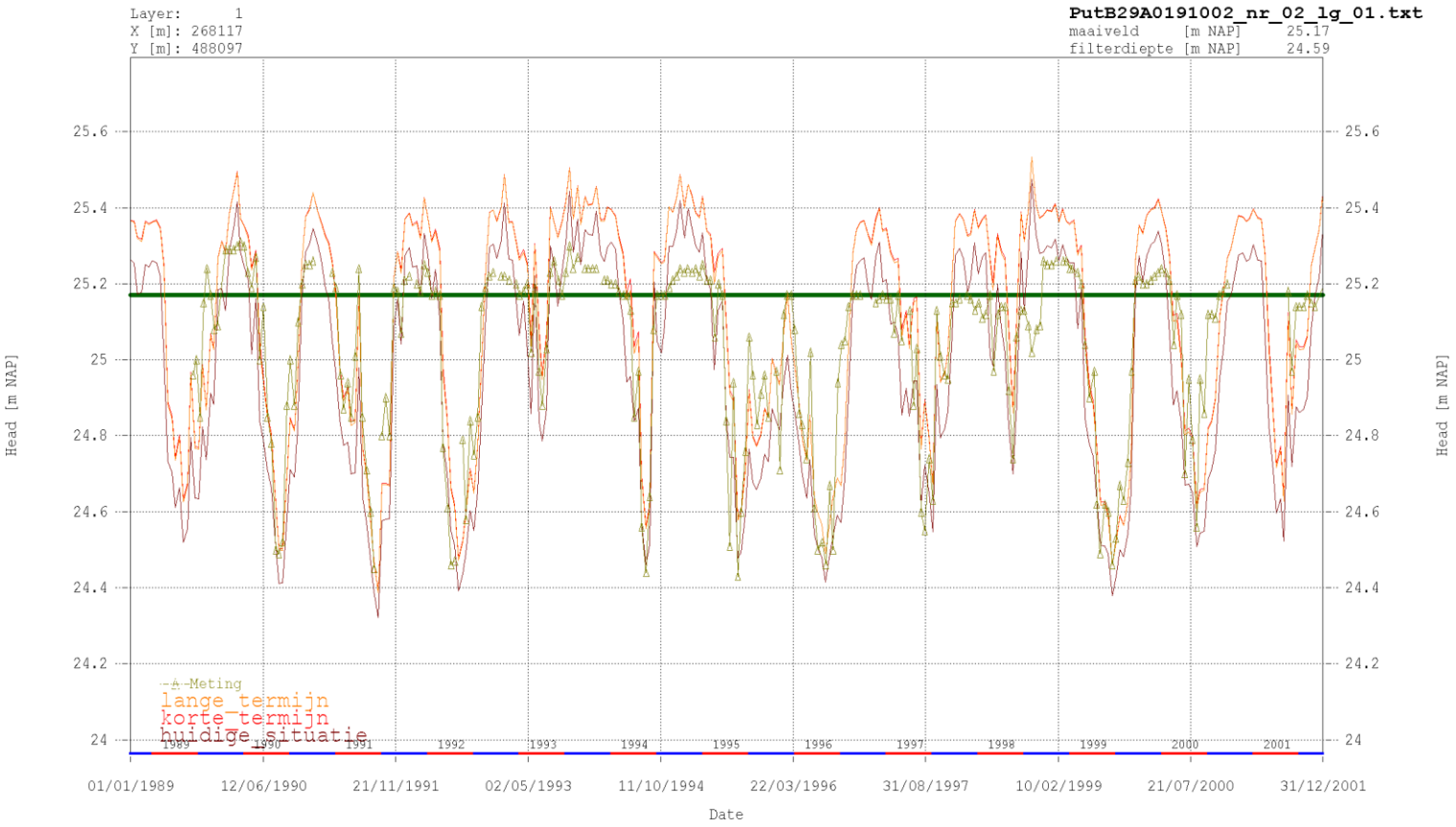
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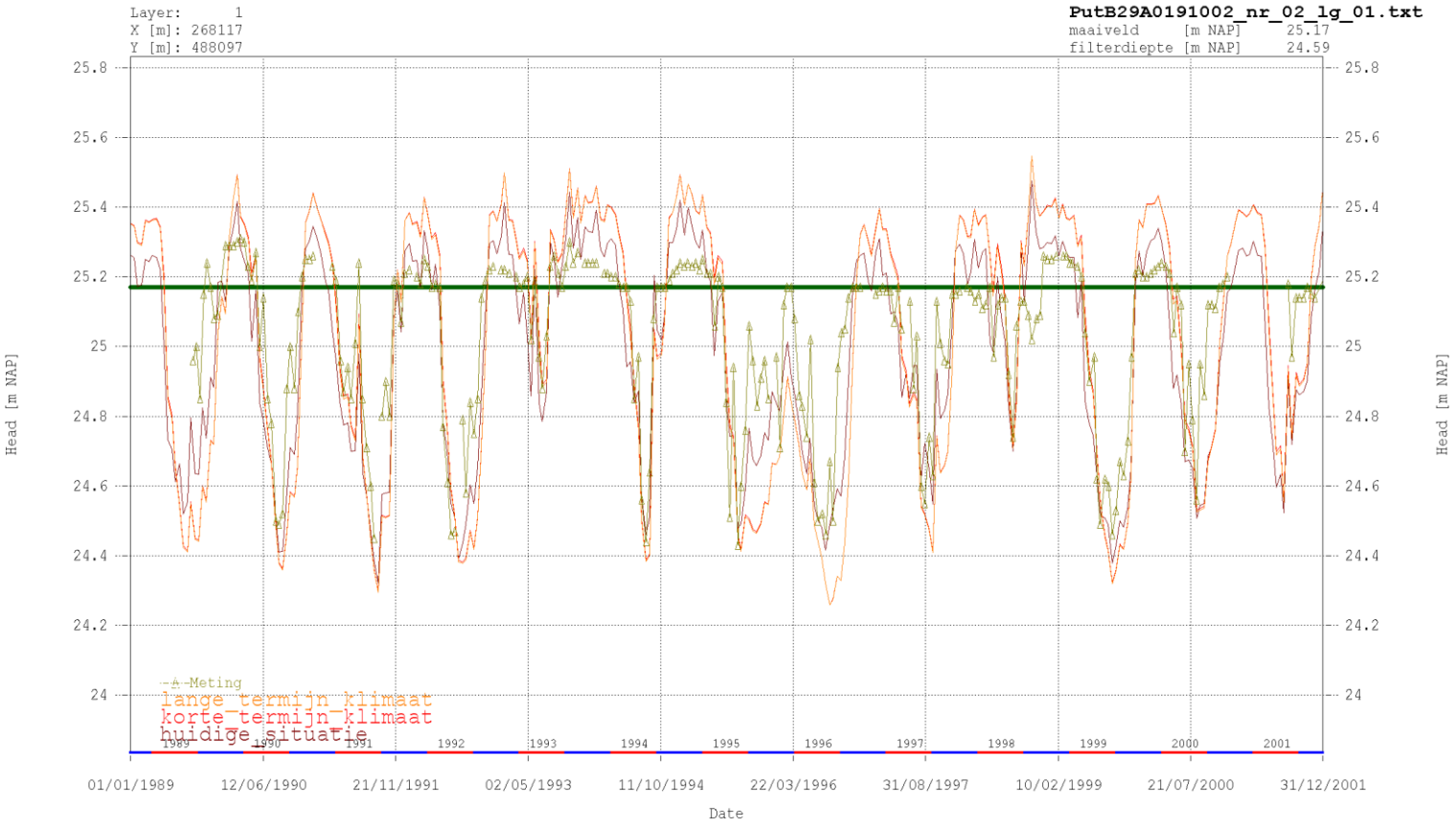
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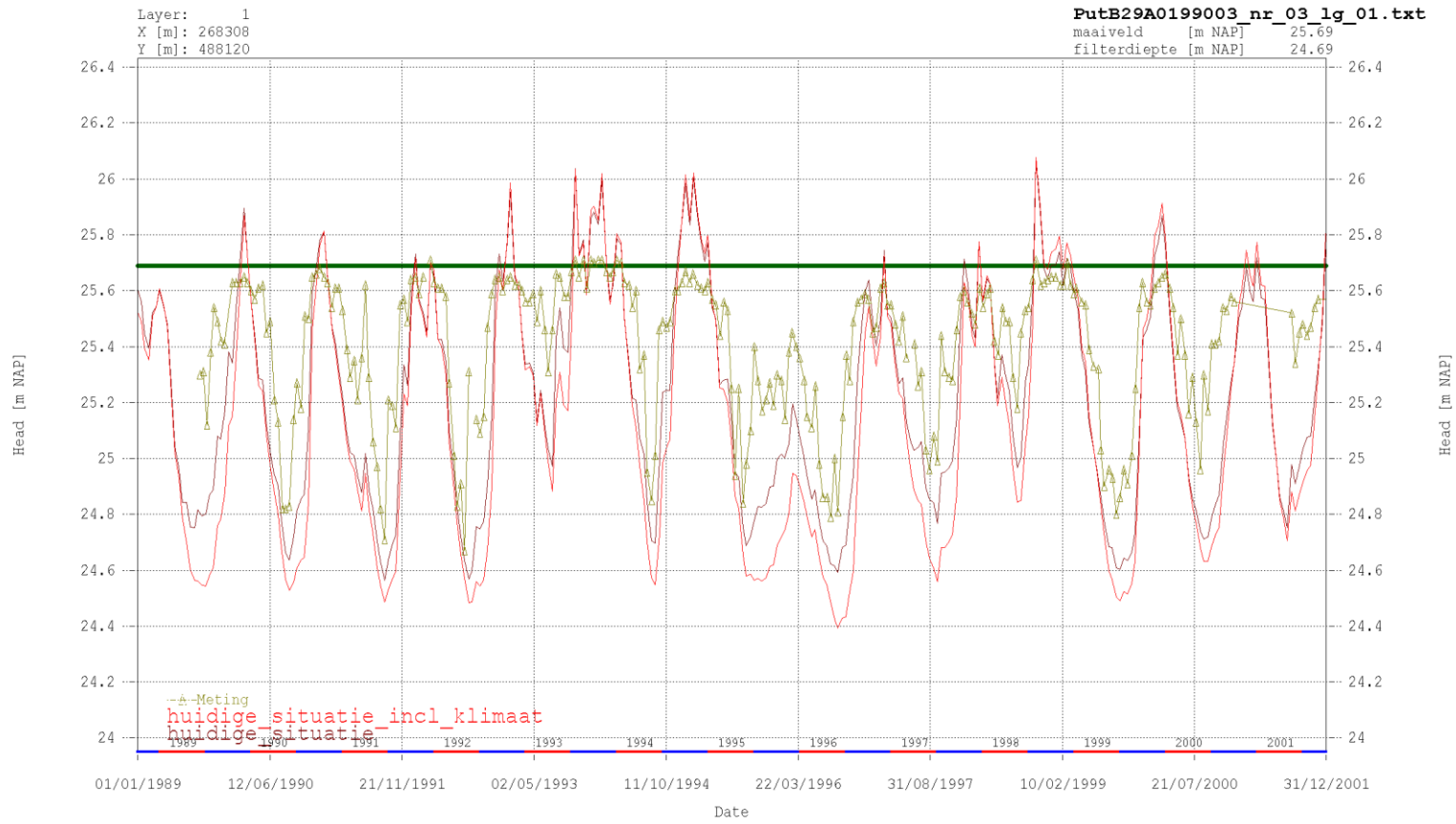
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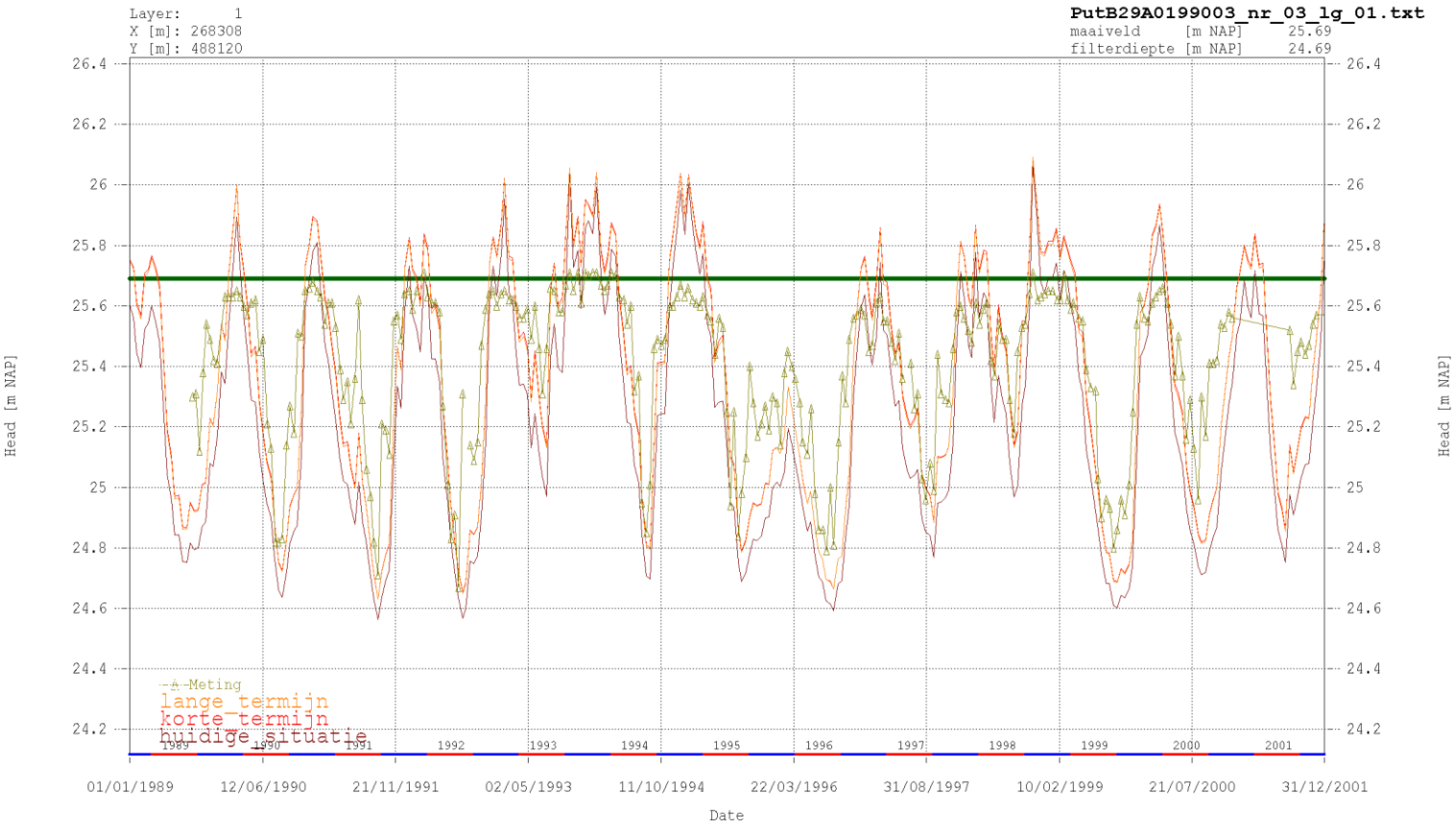
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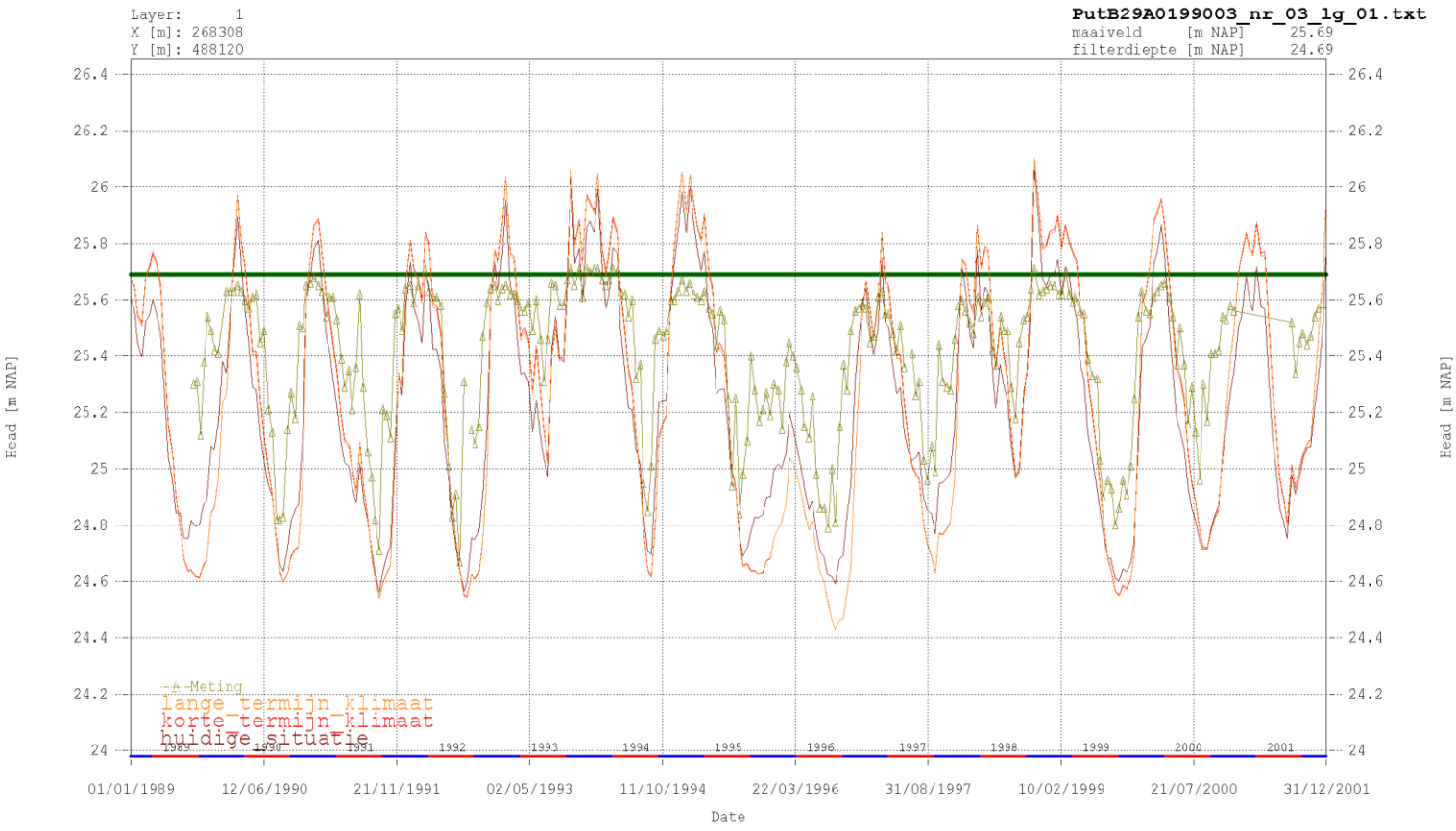
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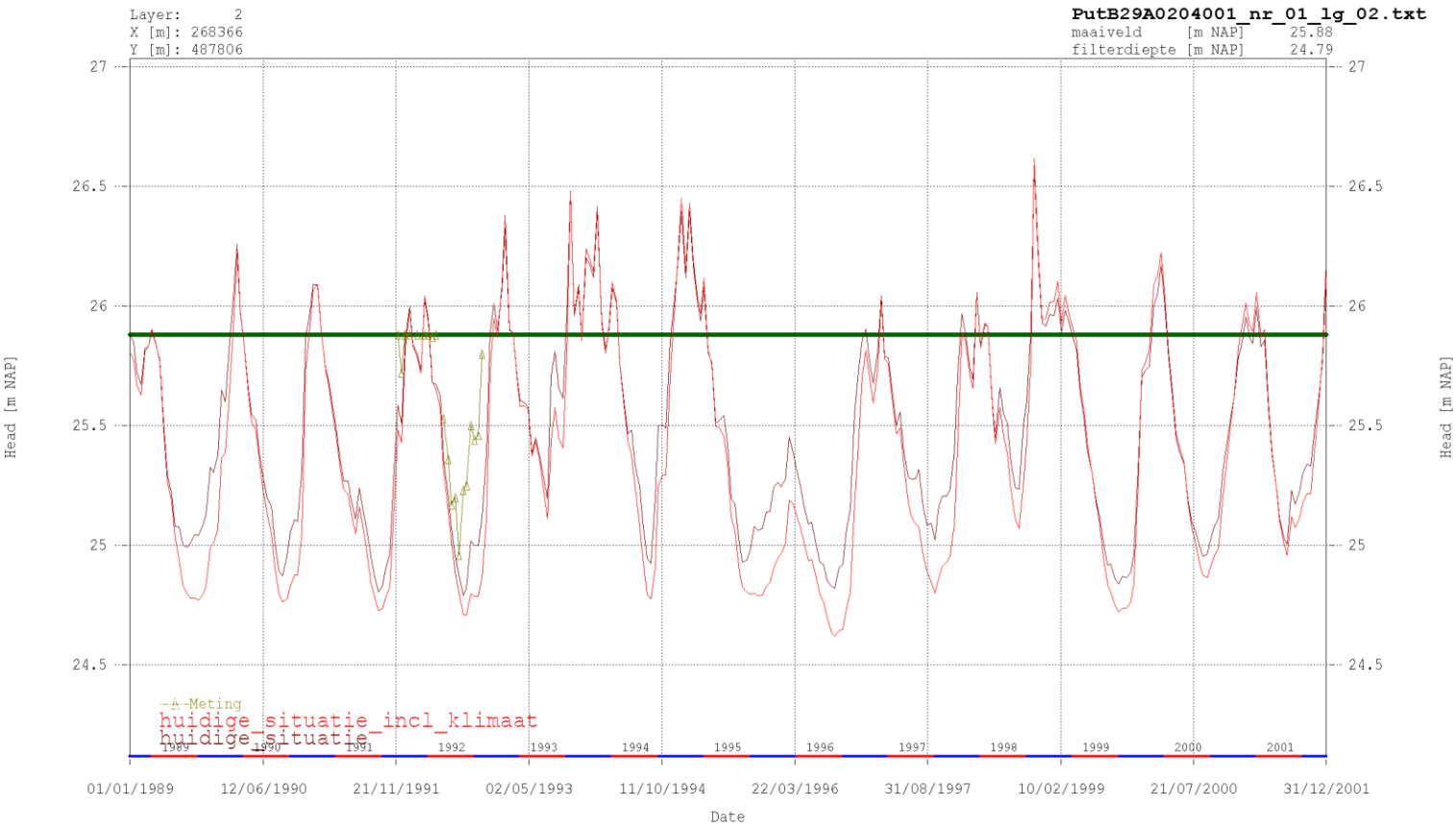
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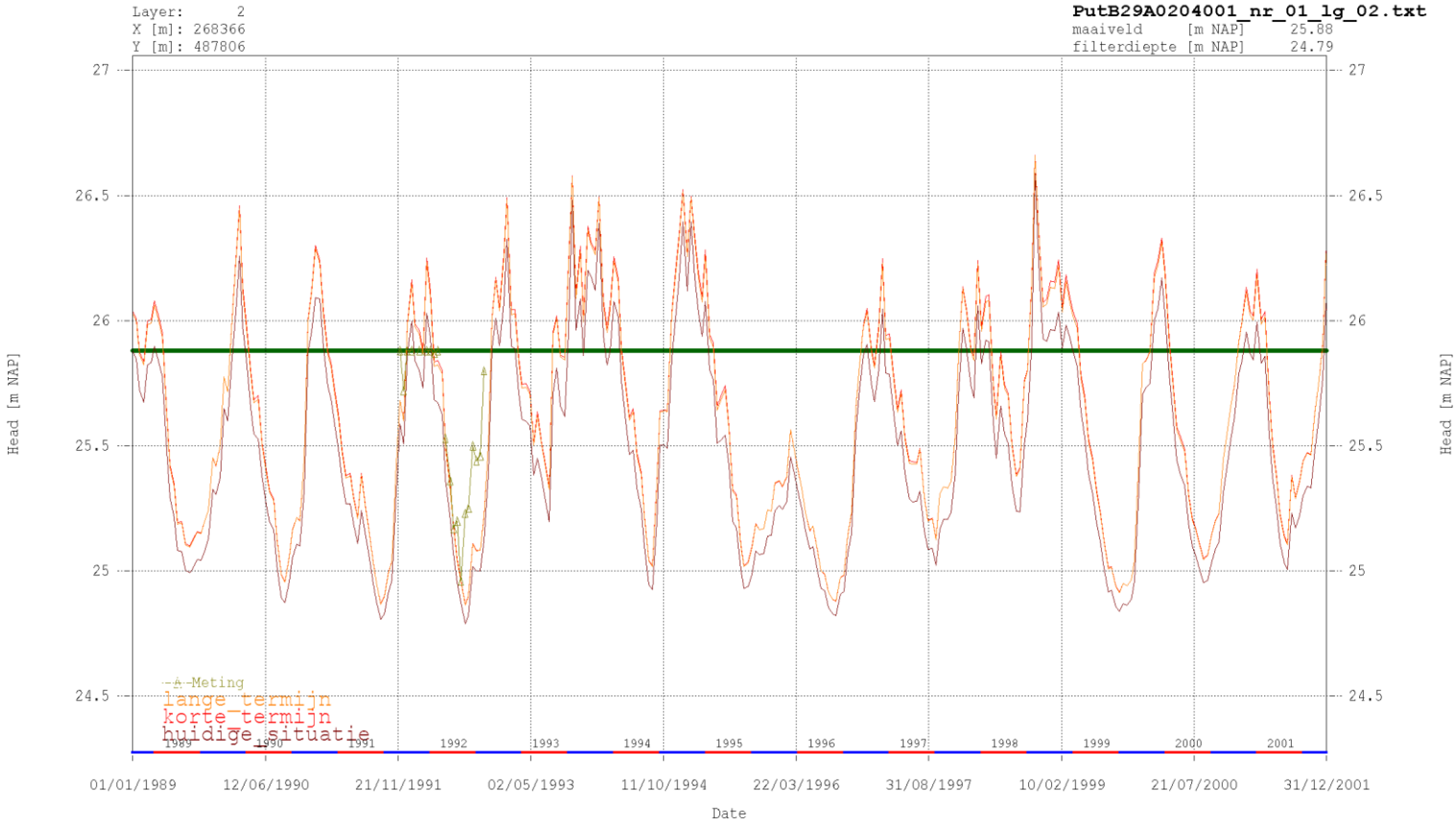
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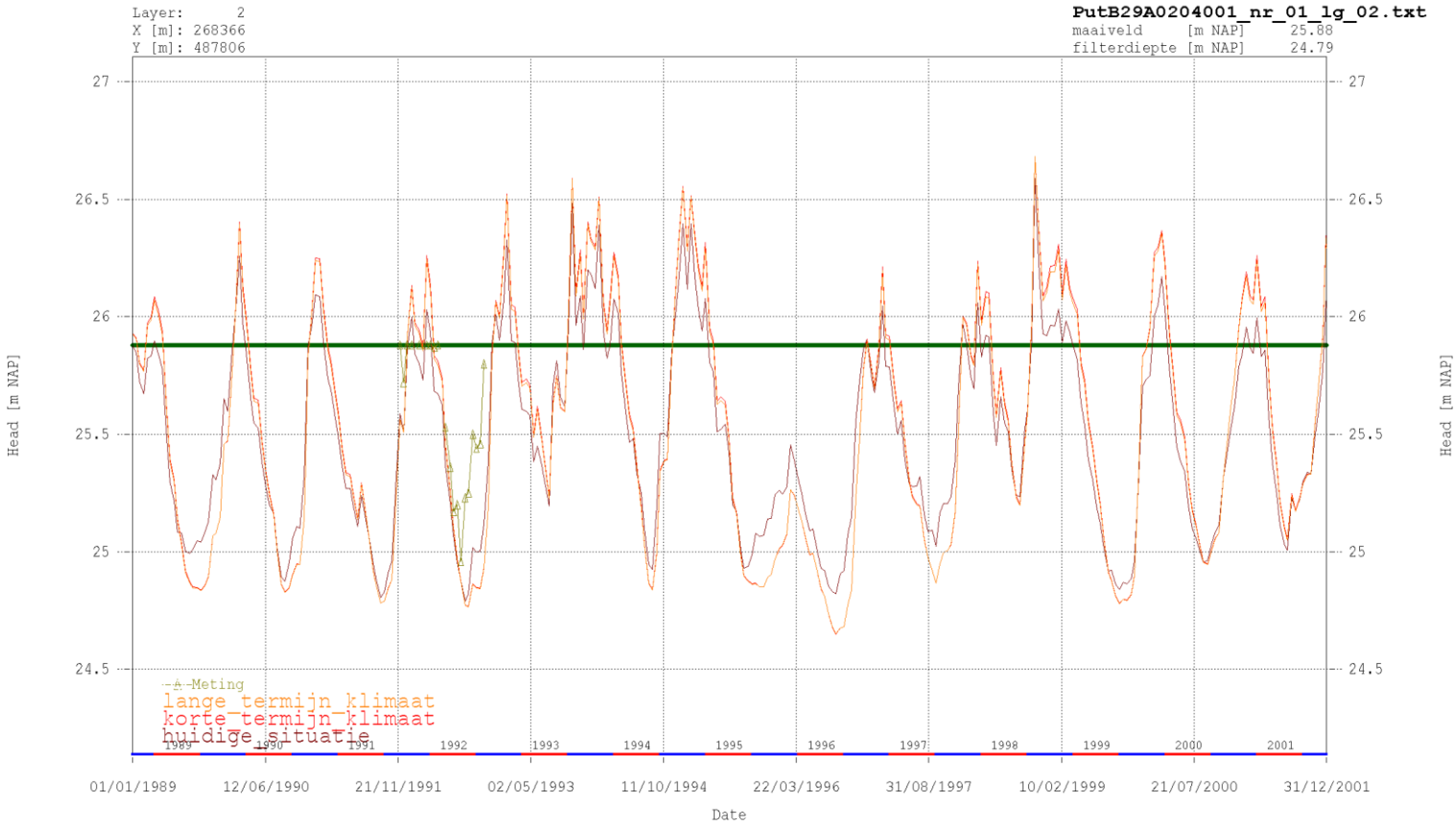
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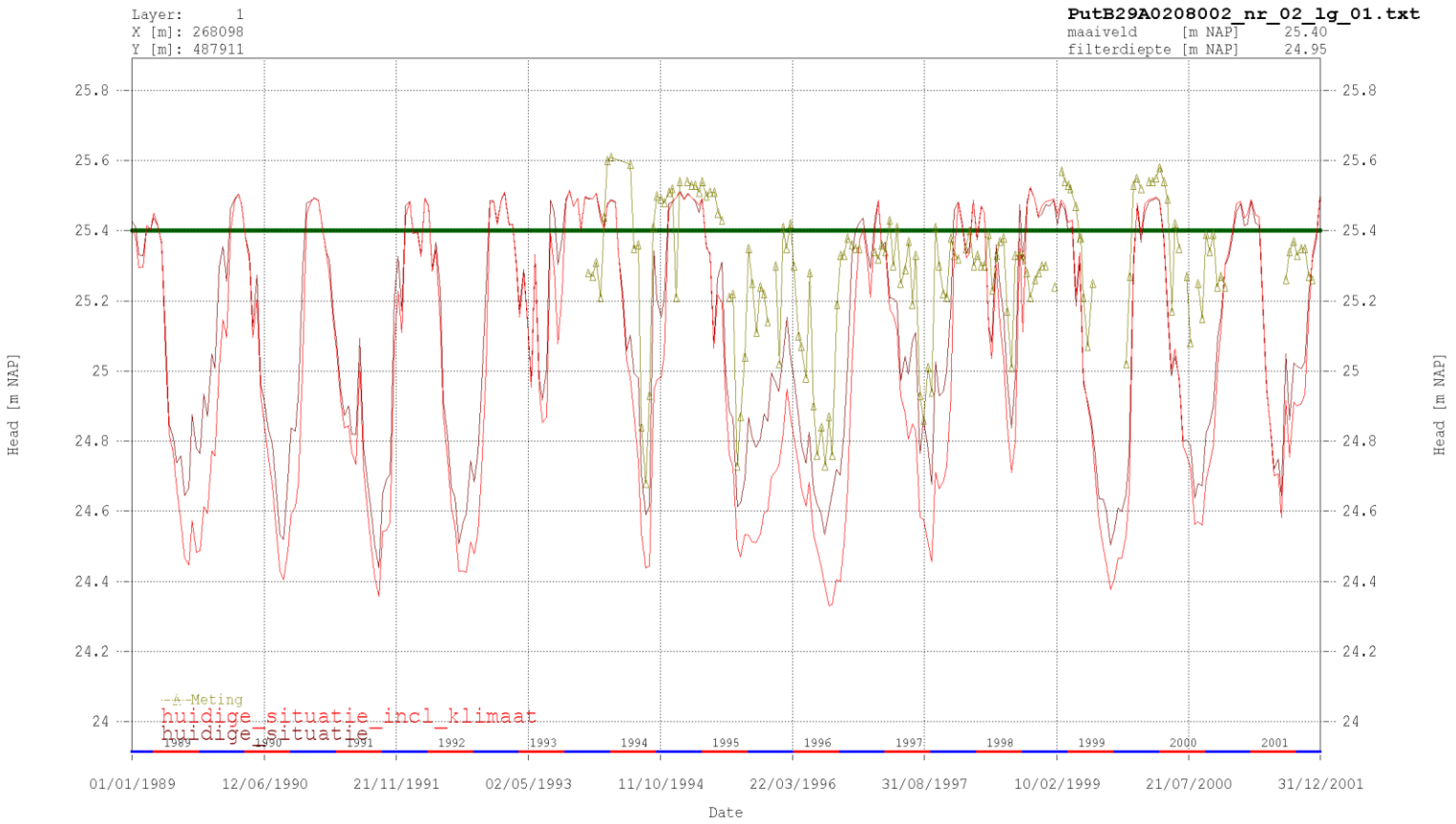
B29A0208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12/06/1990
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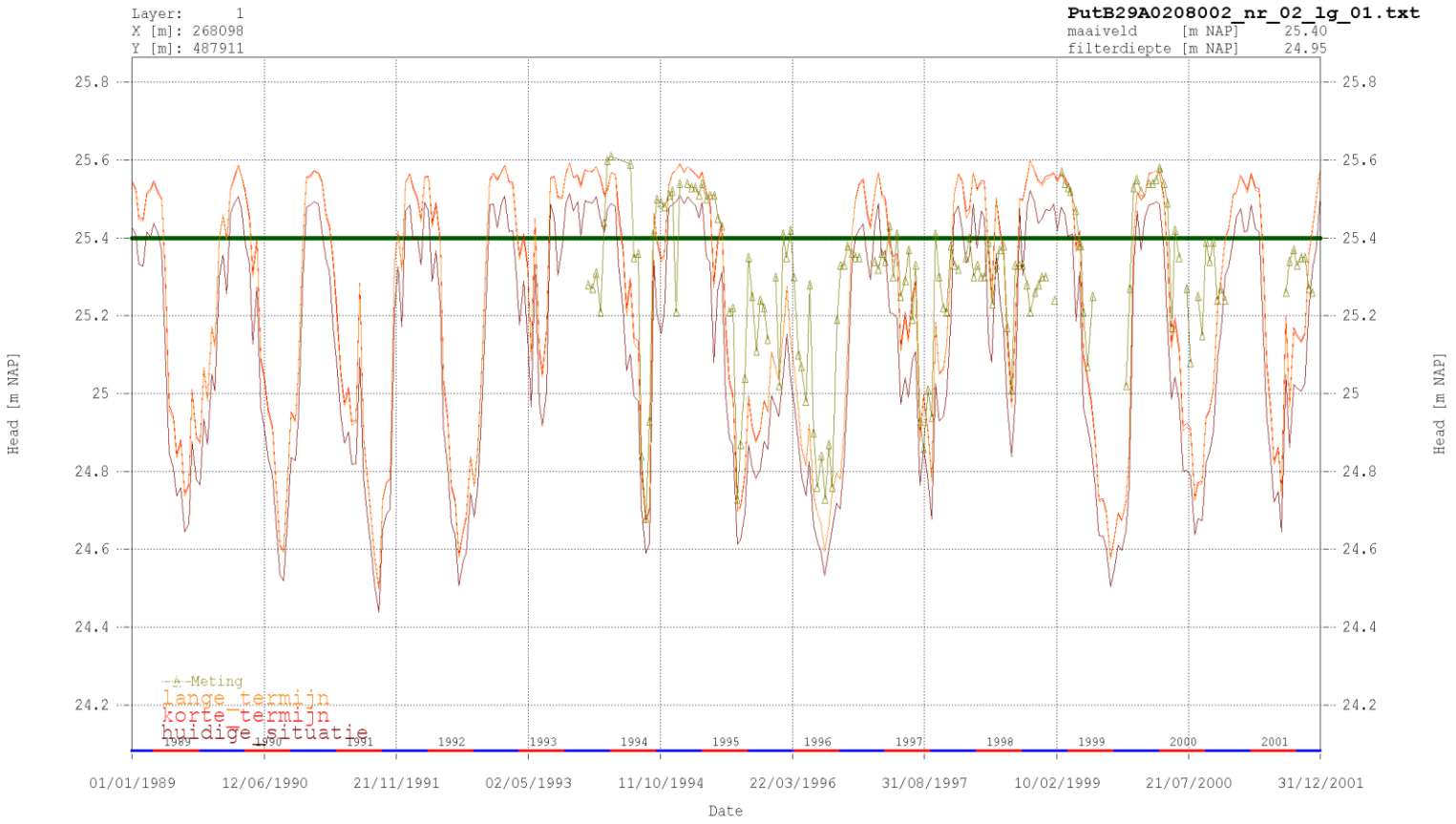
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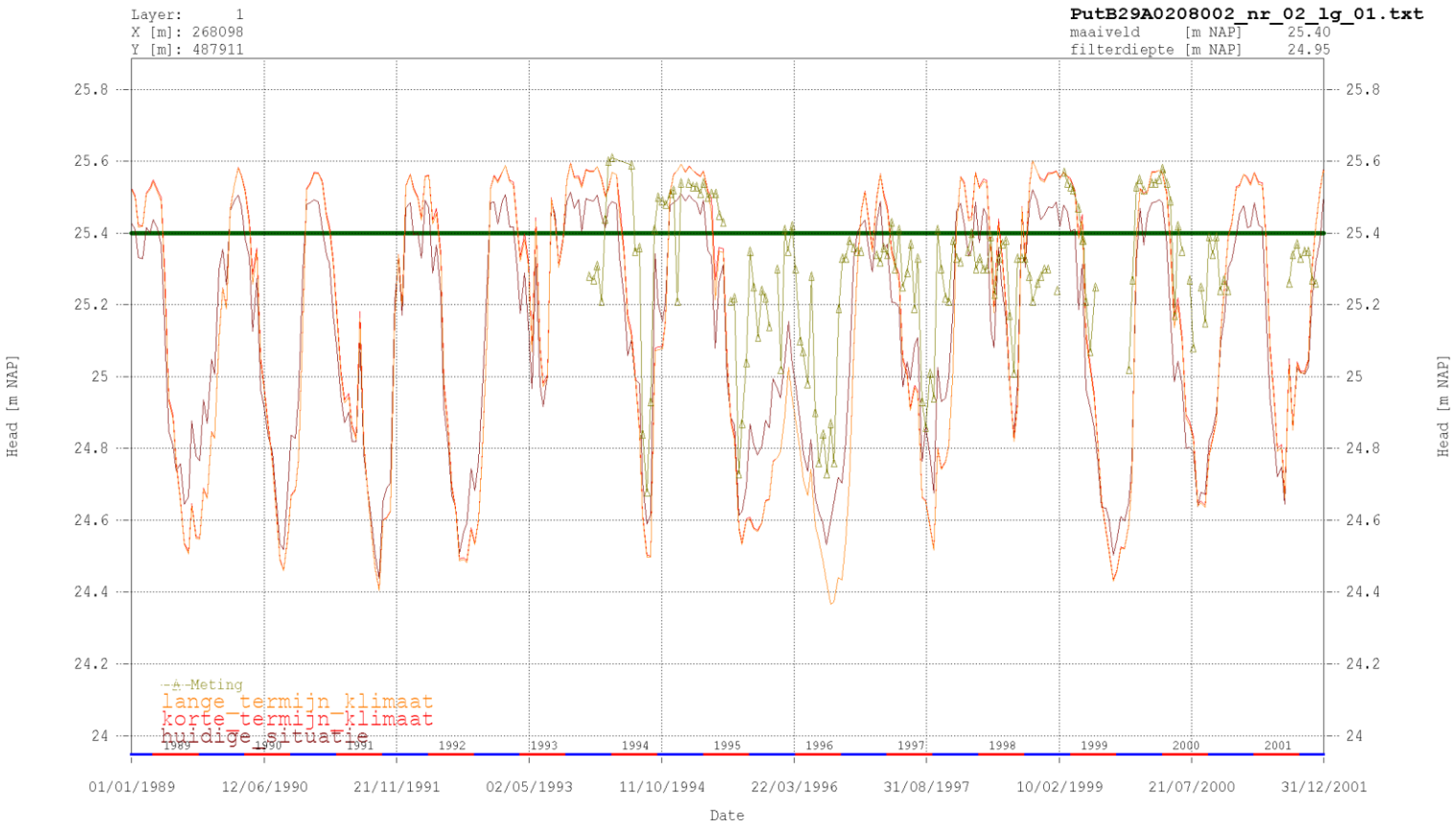
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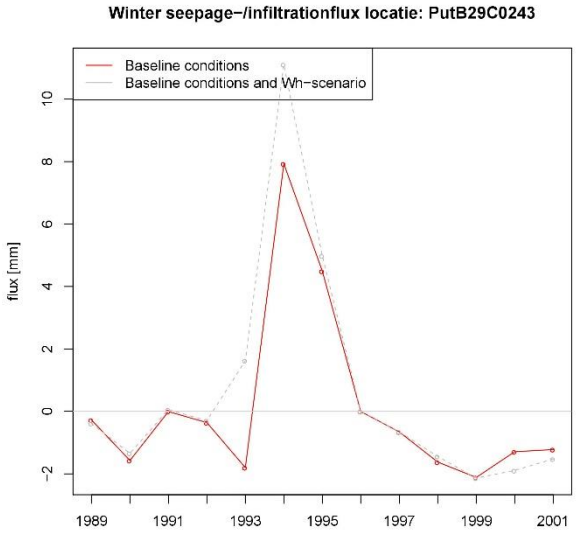
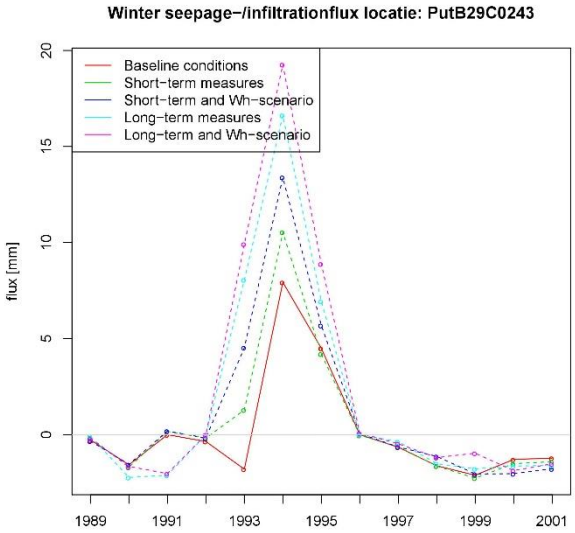
10/02/1999
21/07/2000
31/12/2001
Date

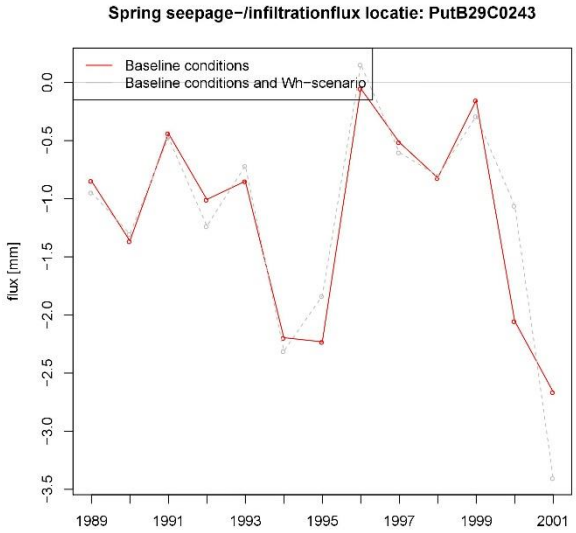
Appendix 4: Winter, spring and summer fluxes for chosen monitoring wells

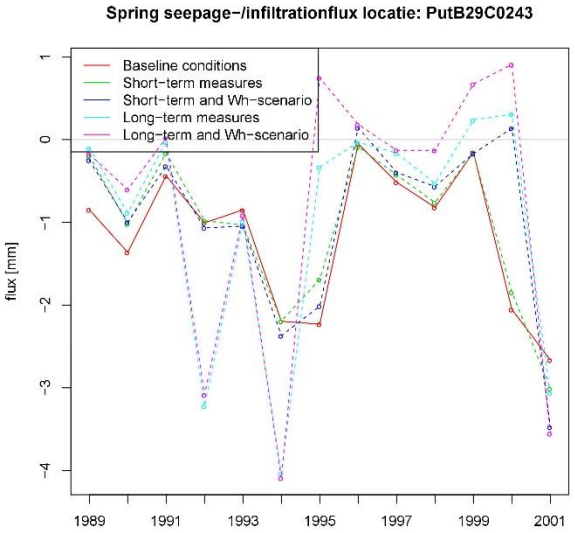
Punthuizen

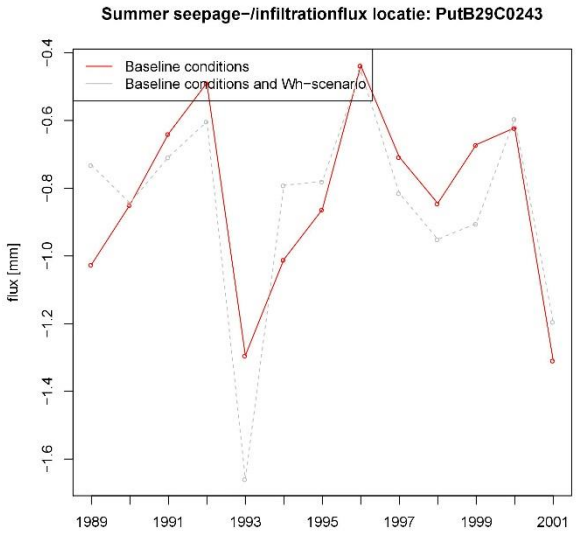
B29C0243 (surface: 28,81 meter above NAP)

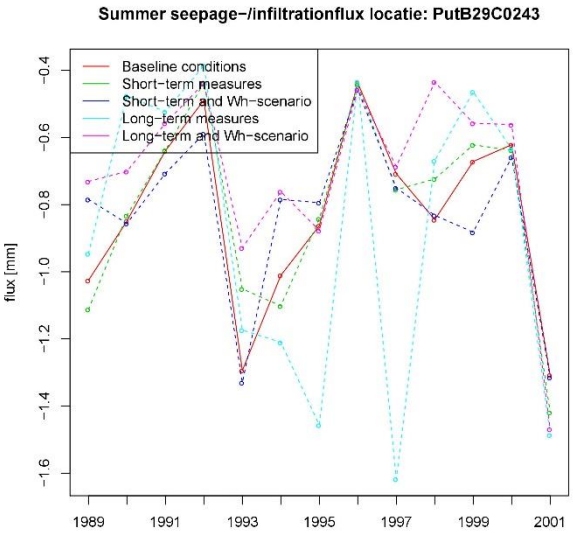




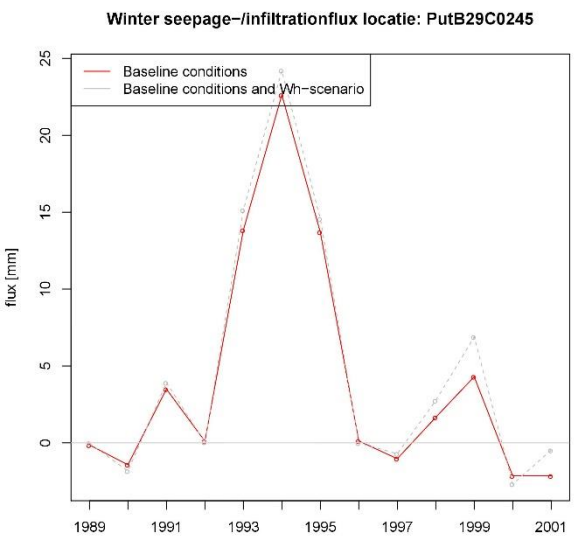


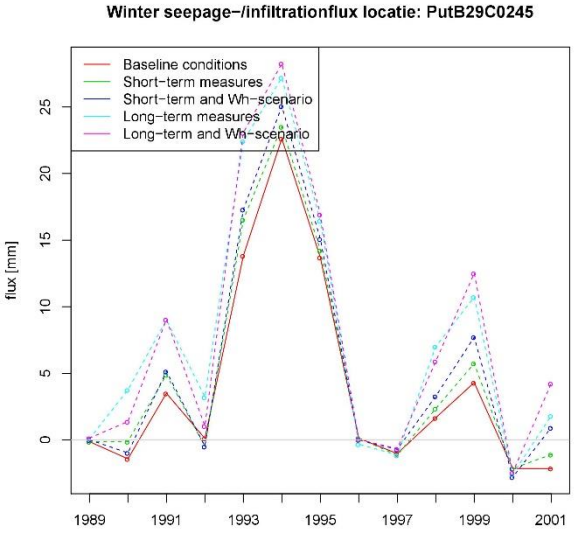


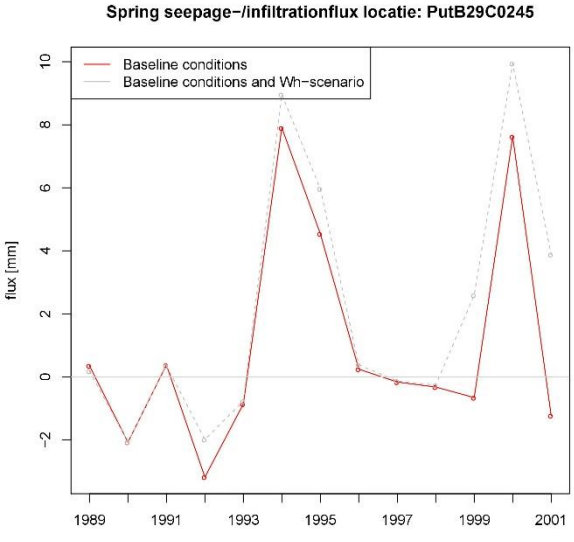


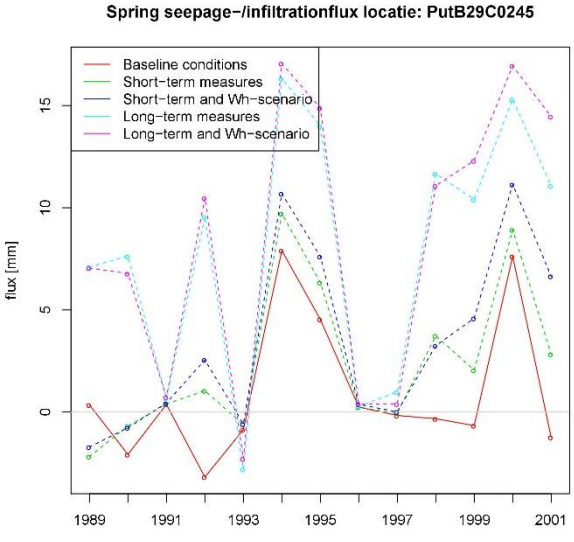


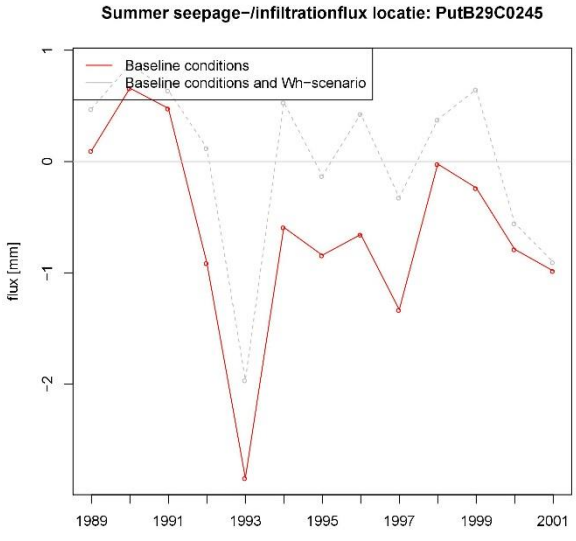
B29C0245 (surface: 28,79 meter above NAP)

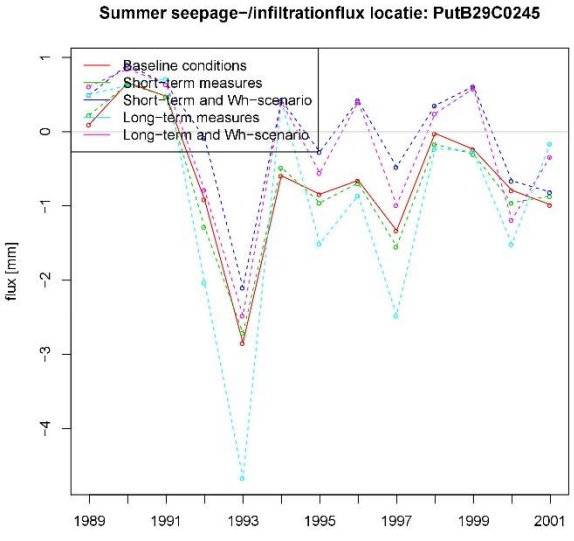




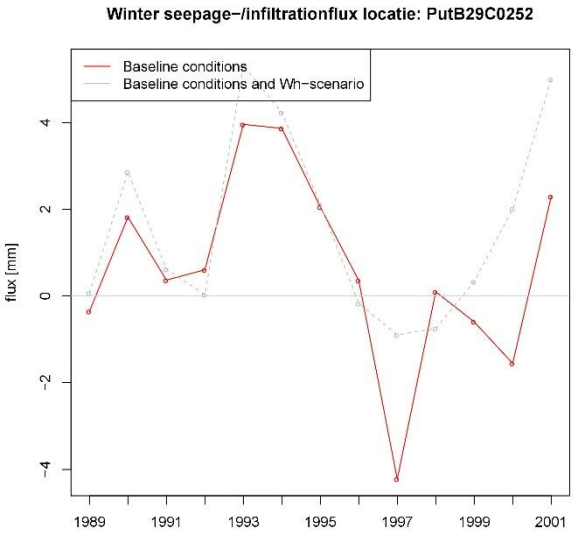


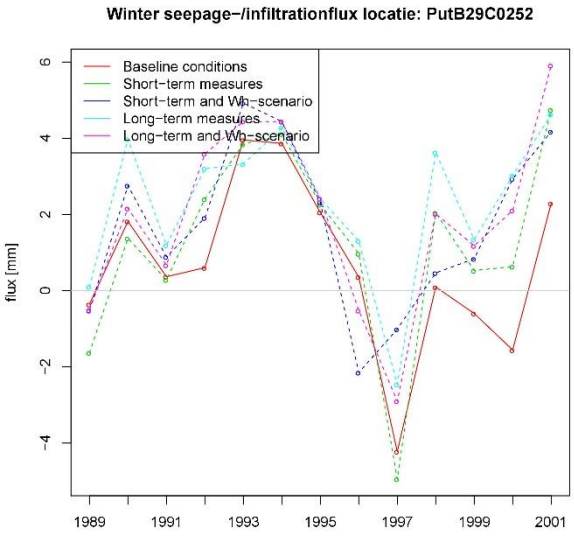


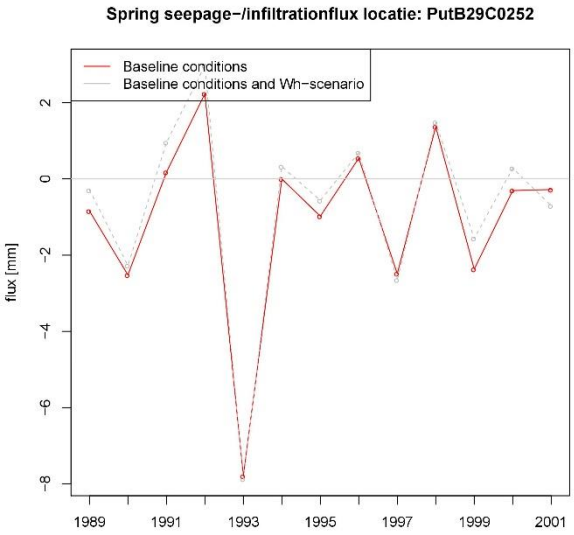


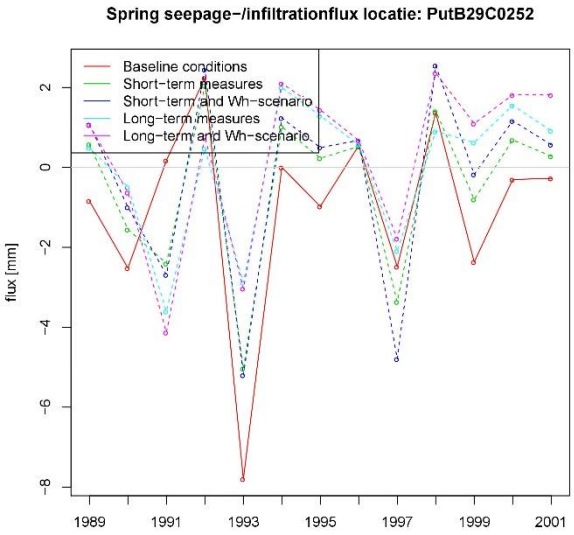


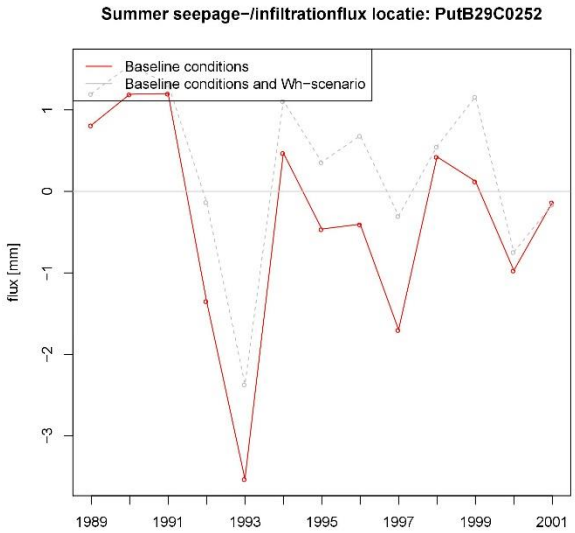
B29C0252 (surface: 28,42 meter above NAP)

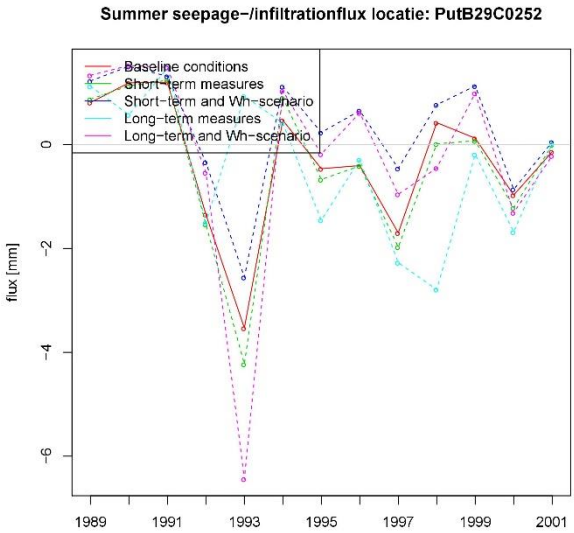






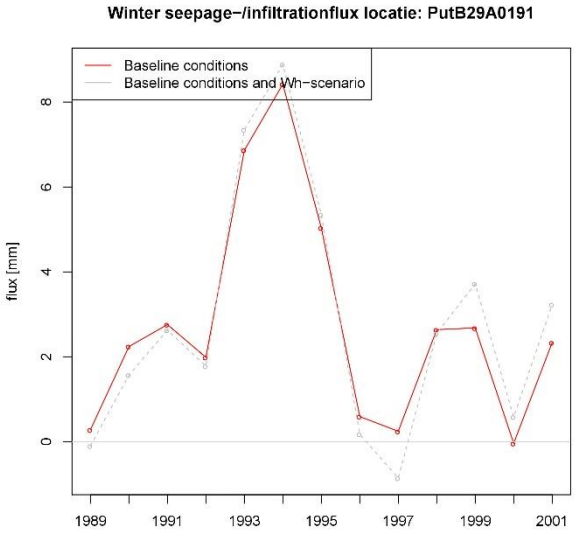


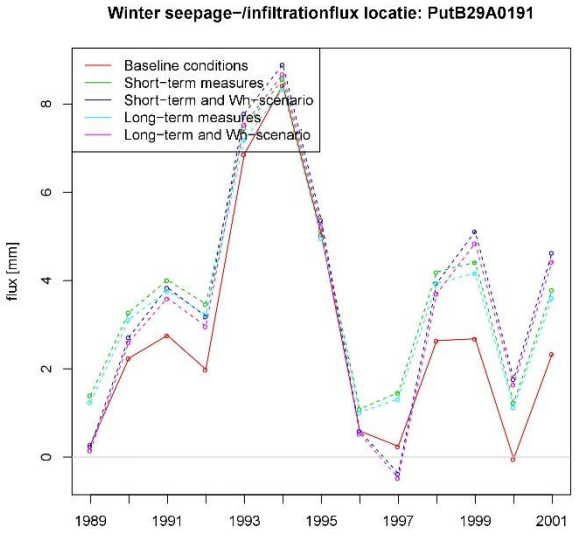


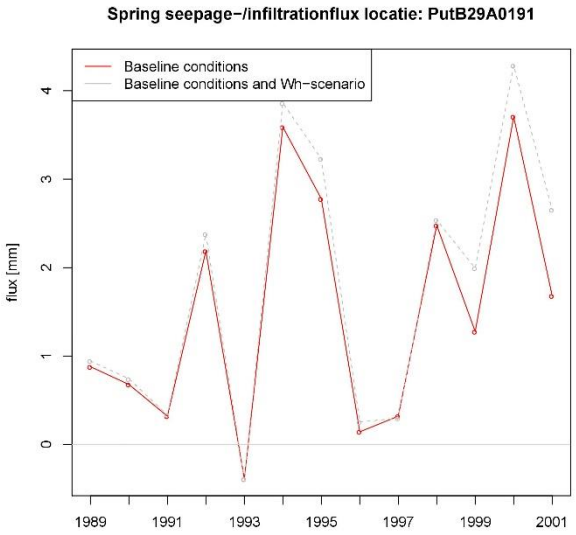


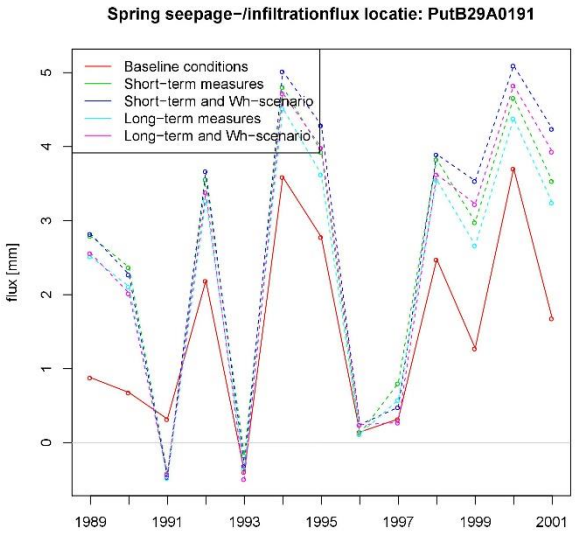
Stroothuizen

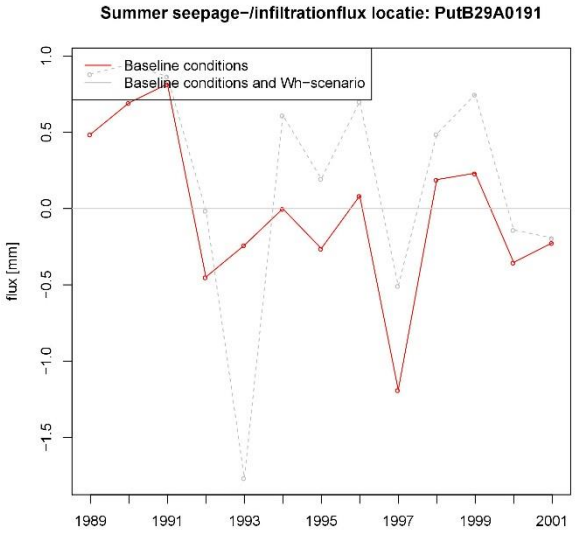
B29A0191 (surface: 25,17 meter above NAP)

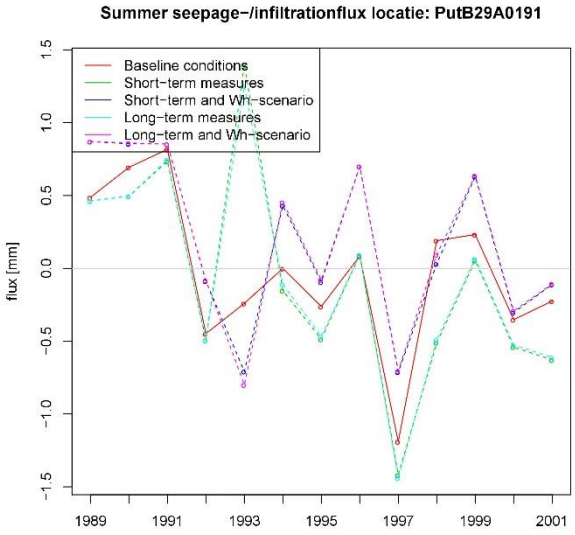




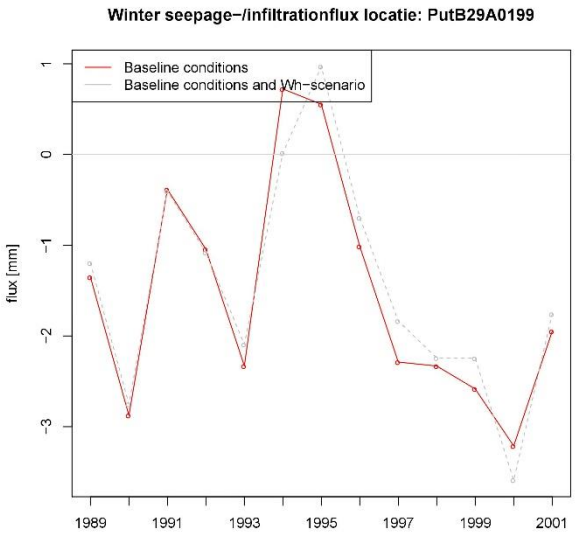


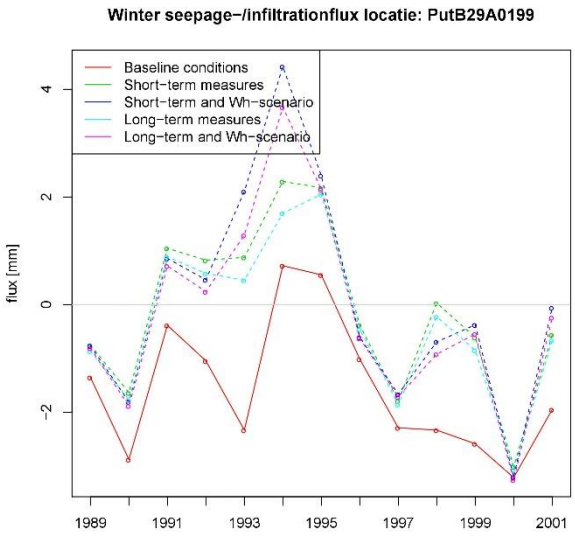


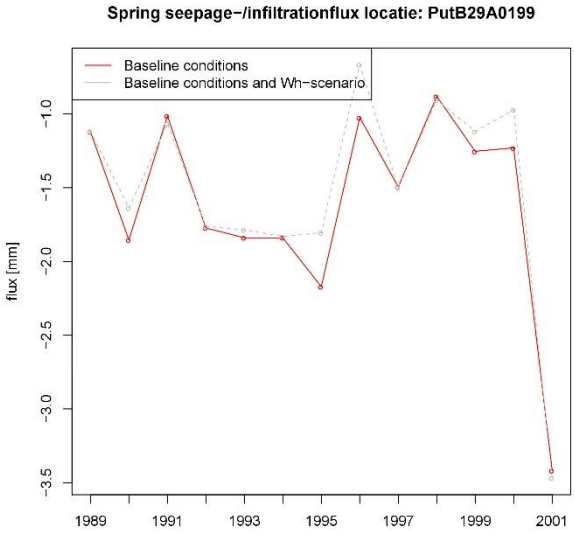


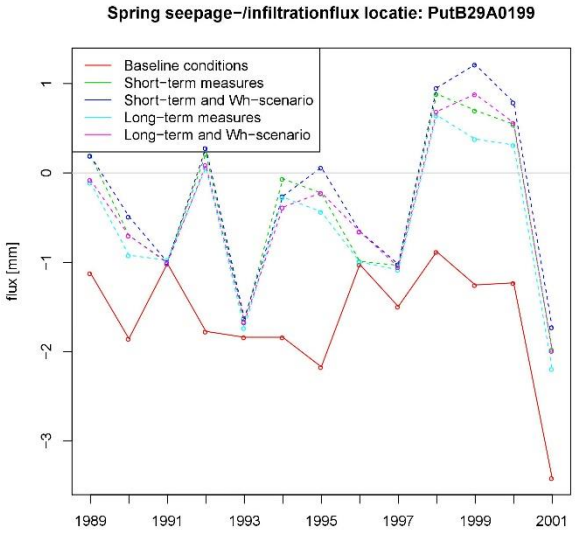


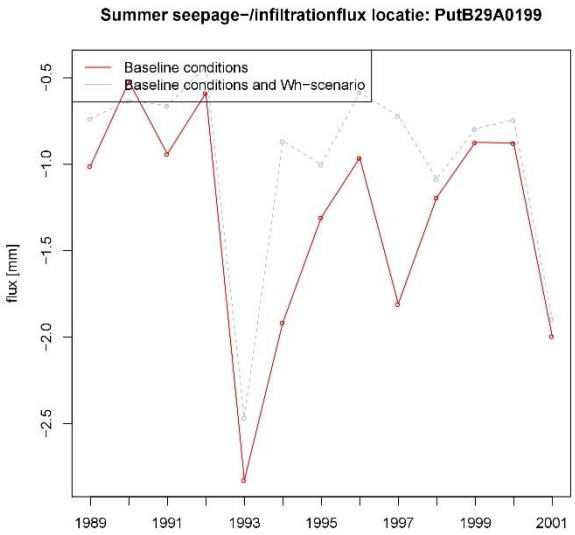
B29A0199 (surface: 25,69 meter above NAP)

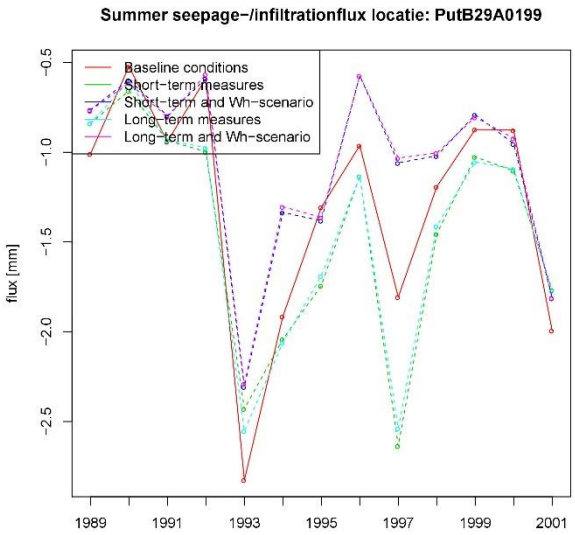




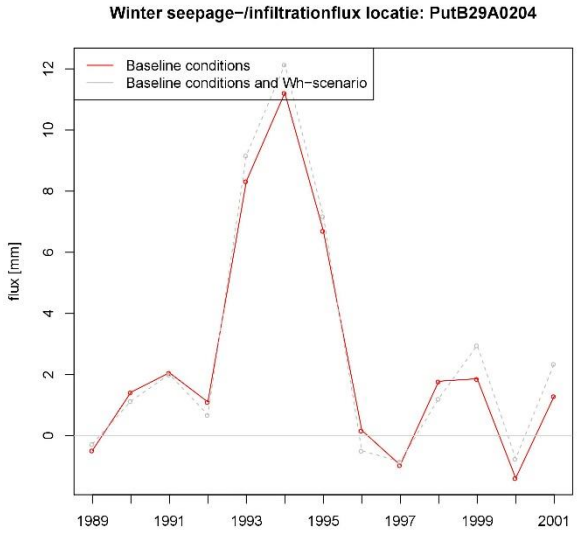


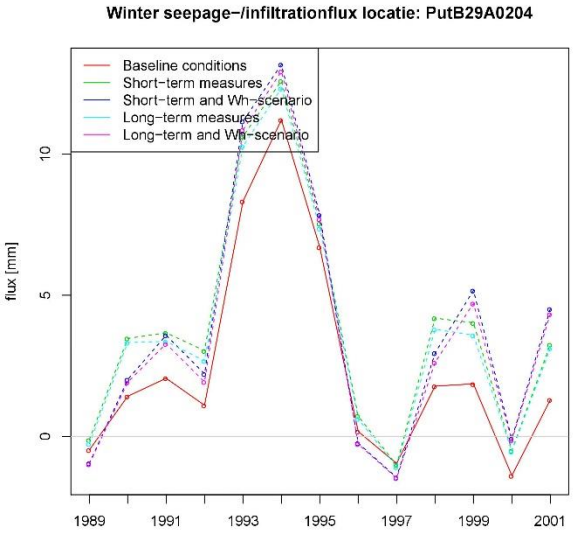


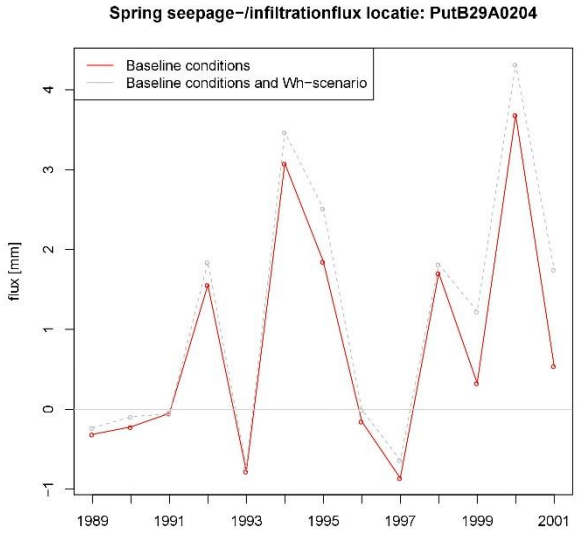


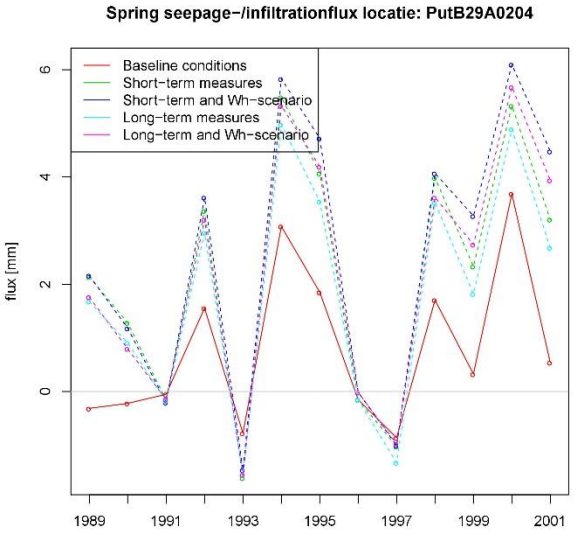


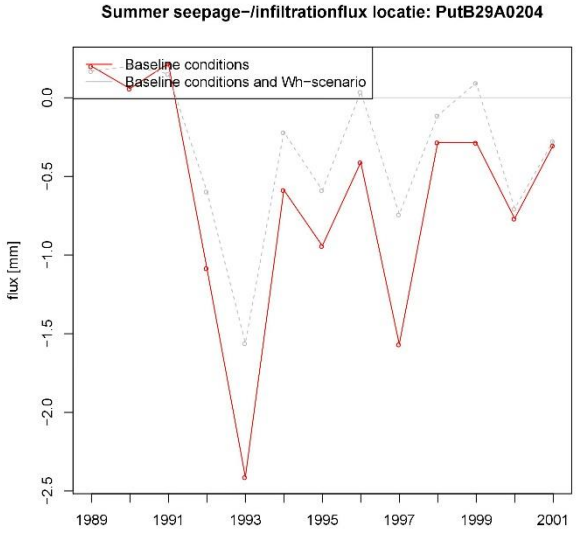
B29A0204 (surface: 25,88 meter above NAP)

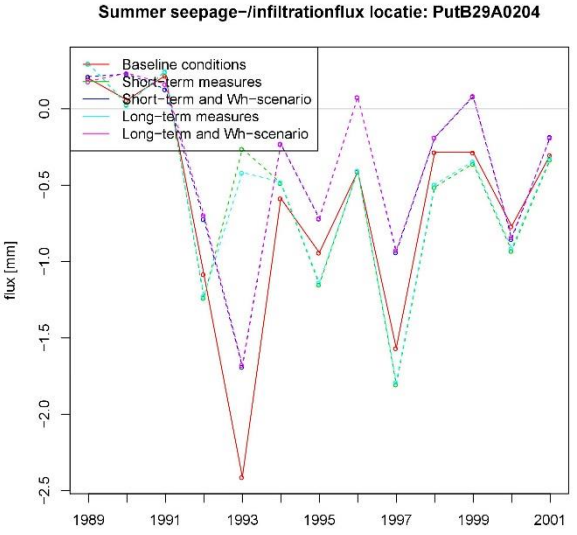




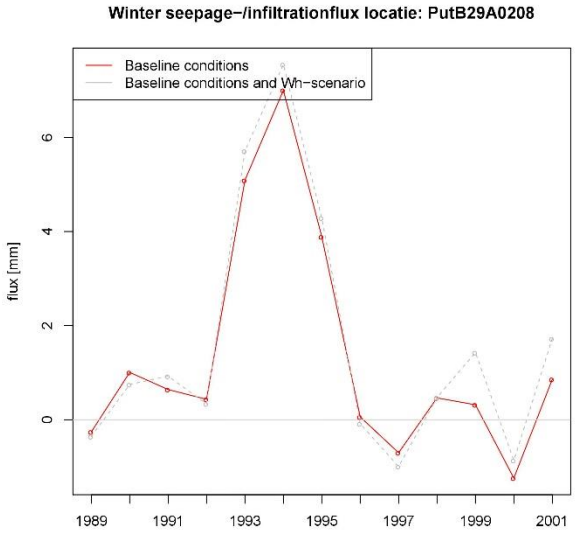


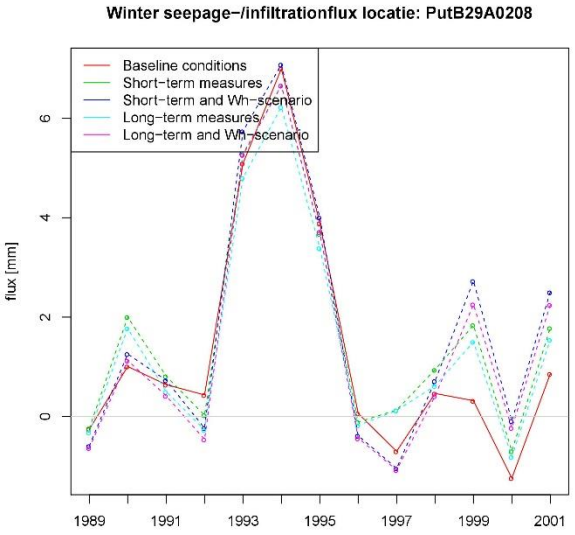


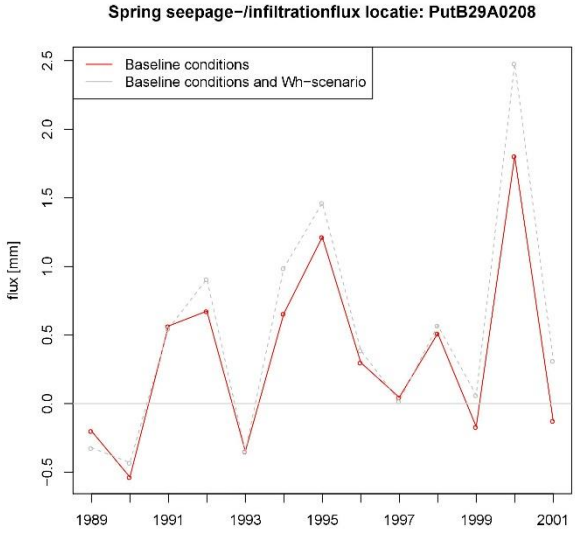


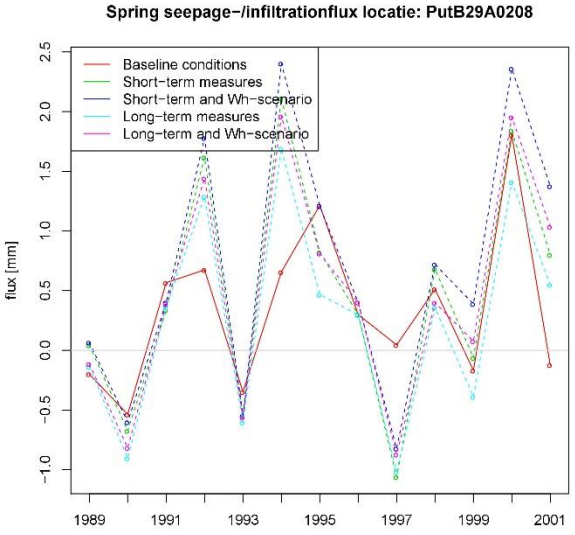


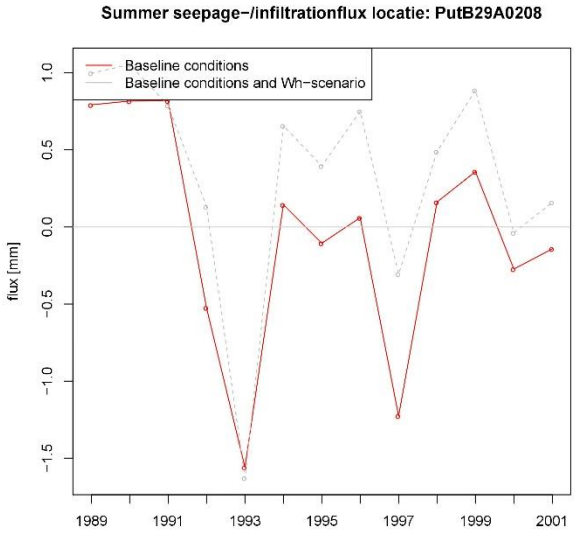
B29A0208 (surface: 25,40 meter above NAP)

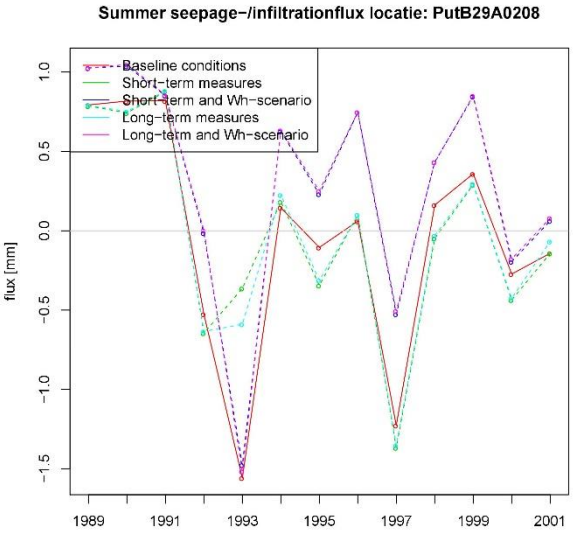












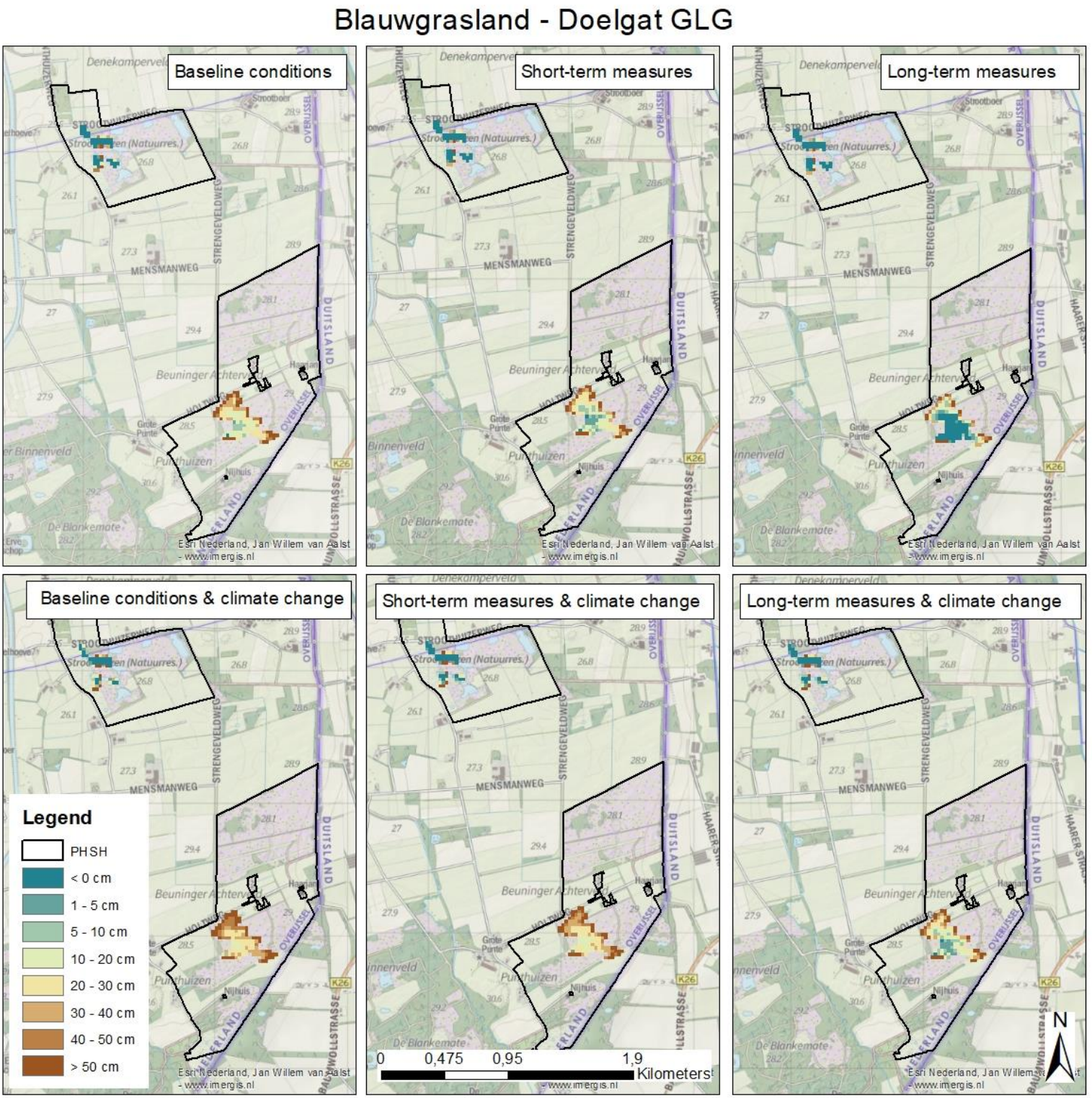
Appendix 5: Extended doelgaten-table including increase/decrease values

Peilbuis			Optimal hydrological conditions (m – mv) GLG	GVG upper	GVG lower	Current situation/baseline (m-mv) GLG	GVG	GHG	Doelgat current situation GLG	GVG	ST measures: change in GXG GHG	GLG	GVG	Doelgat ST-measures GLG	GVG
B29C0252	Blauwgraslanden	Punthuizen	0,9	0,05	0,22	1,10	0,03	-0,18	-0,20	0,19	0,03	0,06	0,04	-0,14	0,23
B29C0245	Blauwgraslanden	Punthuizen	1	0,02	0,15	1,42	0,28	0,10	-0,42	-0,13	0,02	0,05	0,03	-0,37	-0,10
B29C0243	Vochtige heide	Punthuizen	1,5	-0,02	0,25	1,51	0,32	0,13	-0,01	-0,07	0,05	0,06	0,05	0,05	-0,02
B29A0208	Zwakgebufferde ven	Stroothuizen	0,7	-0,35	-0,1	0,63	0,02	-0,09	0,07	-0,12	0,09	0,10	0,09	0,17	-0,03
B29A0204	Pioniersvegetaties met Snavelbiezen	Stroothuizen		-0,1	0,4	0,62	0,05	-0,05		0,35	0,09	0,10	0,09		0,44
B29A0199	Vochtige heide	Stroothuizen	1,5	-0,02	0,25	0,73	0,13	0,02	0,77	0,12	0,11	0,11	0,11	0,88	0,23
B29A0191	Blauwgraslanden	Stroothuizen	0,7	-0,35	-0,1	0,53	-0,03	-0,15	0,17	-0,07	0,08	0,12	0,09	0,29	0,02

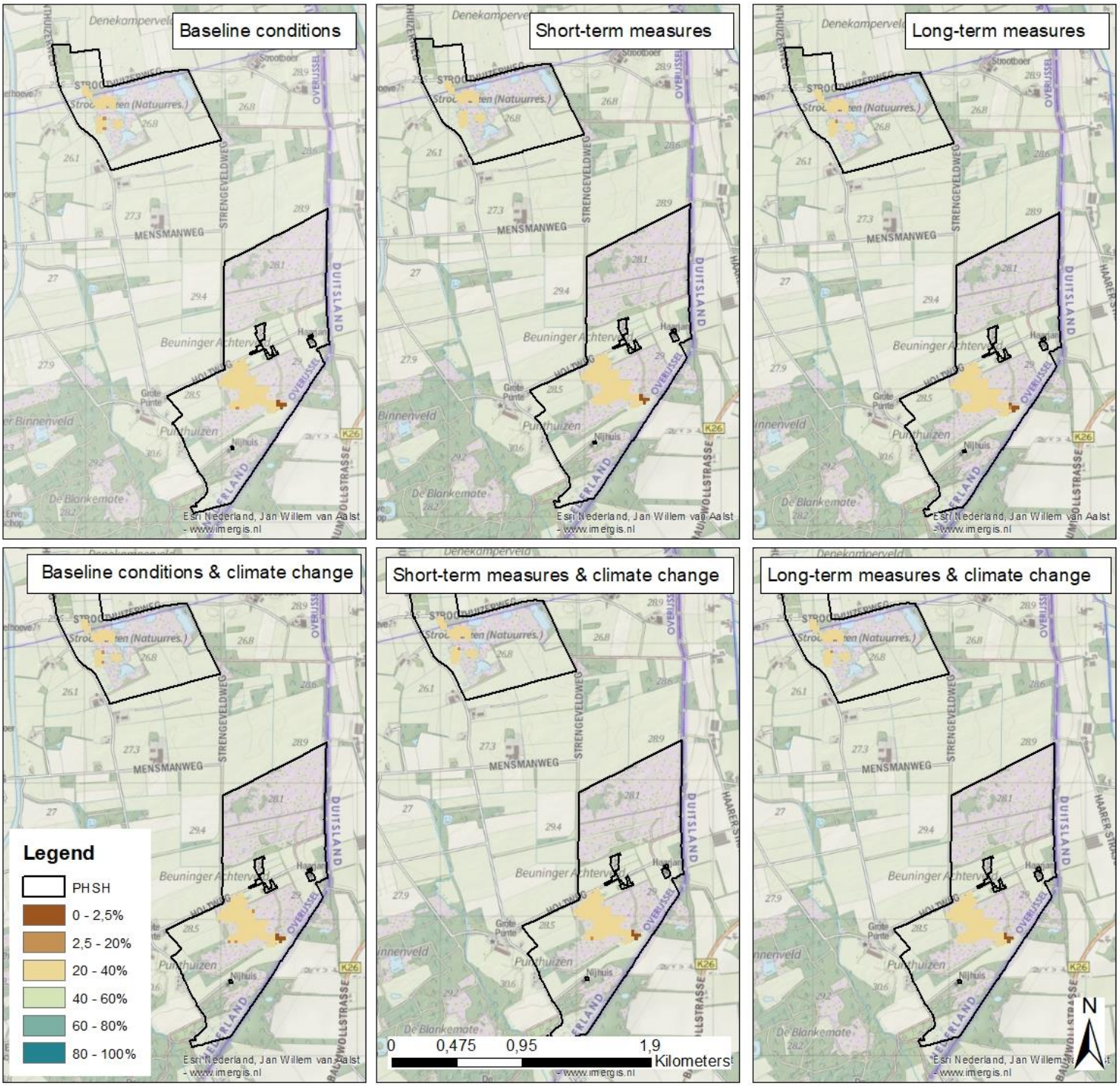
ST + Wh: change in GXG GHG	GLG	GVG	Doelgat ST + Wh GLG	GVG	LT measures: change in GXG GHG	GLG	GVG	Doelgat LT + Wh GLG	GVG	LT + Wh: change in GXG GHG	GLG	GVG	Doelgat LT + Wh GLG	GVG
0,01	-0,07	0,00	-0,27	0,19	0,07	0,22	0,10	0,02	0,29	0,04	0,06	0,05	-0,14	0,24
0,01	-0,06	-0,01	-0,48	-0,14	0,05	0,22	0,08	-0,20	-0,05	0,03	0,07	0,04	-0,35	-0,09
0,04	-0,06	0,02	-0,07	-0,05	0,12	0,21	0,13	0,20	0,06	0,10	0,06	0,09	0,05	0,02
0,08	-0,06	0,05	0,01	-0,07	0,09	0,09	0,09	0,16	-0,03	0,08	-0,07	0,05	0,00	-0,07
0,07	-0,06	0,05		0,40	0,08	0,10	0,09		0,44	0,07	-0,06	0,04		0,39
0,10	-0,04	0,08	0,73	0,20	0,10	0,11	0,10	0,88	0,22	0,09	-0,04	0,07	0,73	0,19
0,08	-0,04	0,06	0,13	-0,01	0,08	0,12	0,09	0,29	0,02	0,08	-0,05	0,05	0,12	-0,02

Appendix 6: Maps displaying doelgat GLG, target realization transpiration stress, doelgat GVG and target realization oxygen stress per vegetation type

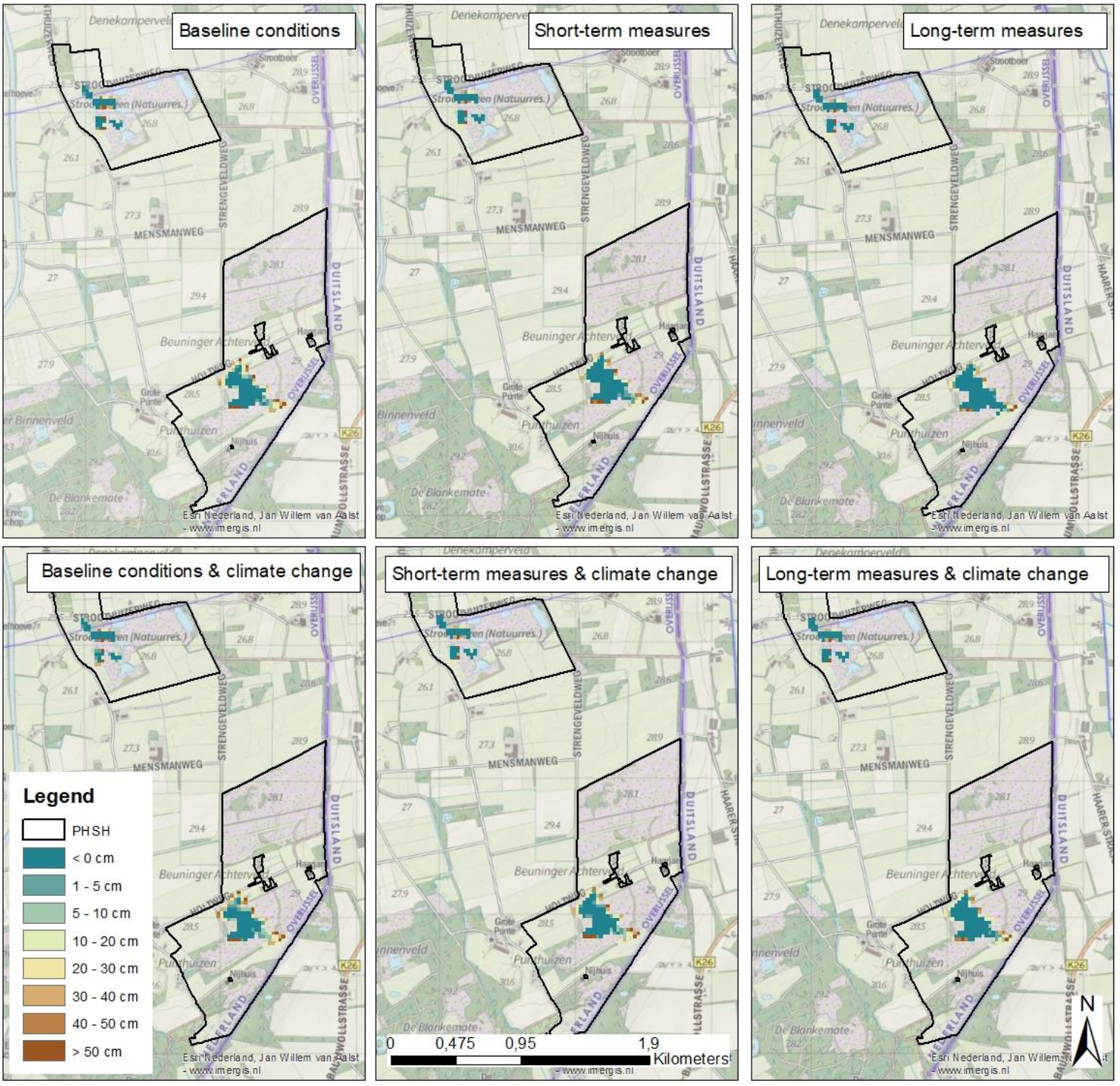
Blauwgrasland



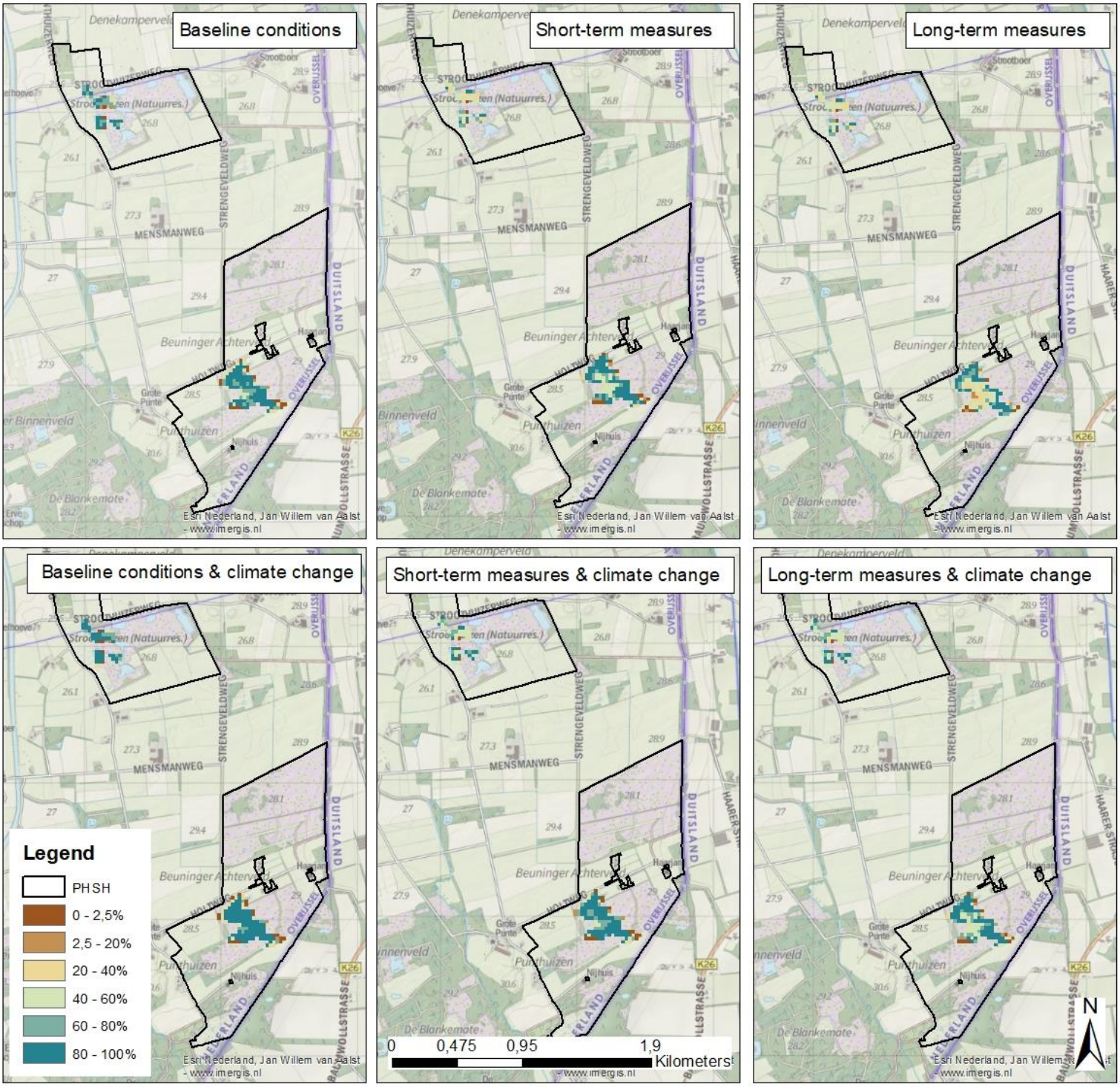
Blauwgrasland - Target Realization Transpiration Stress



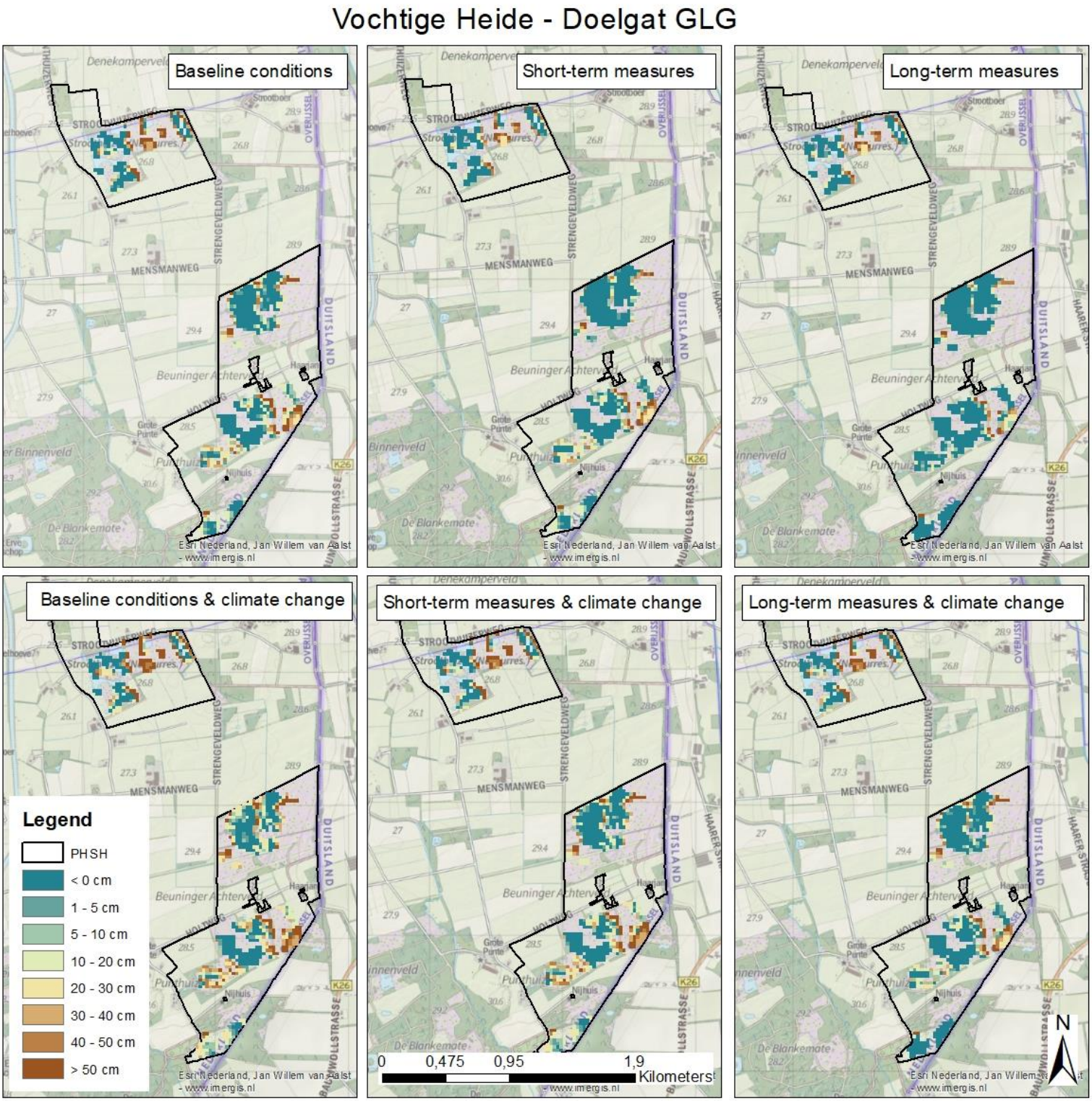
Blauwgrasland - Doelgat GVG



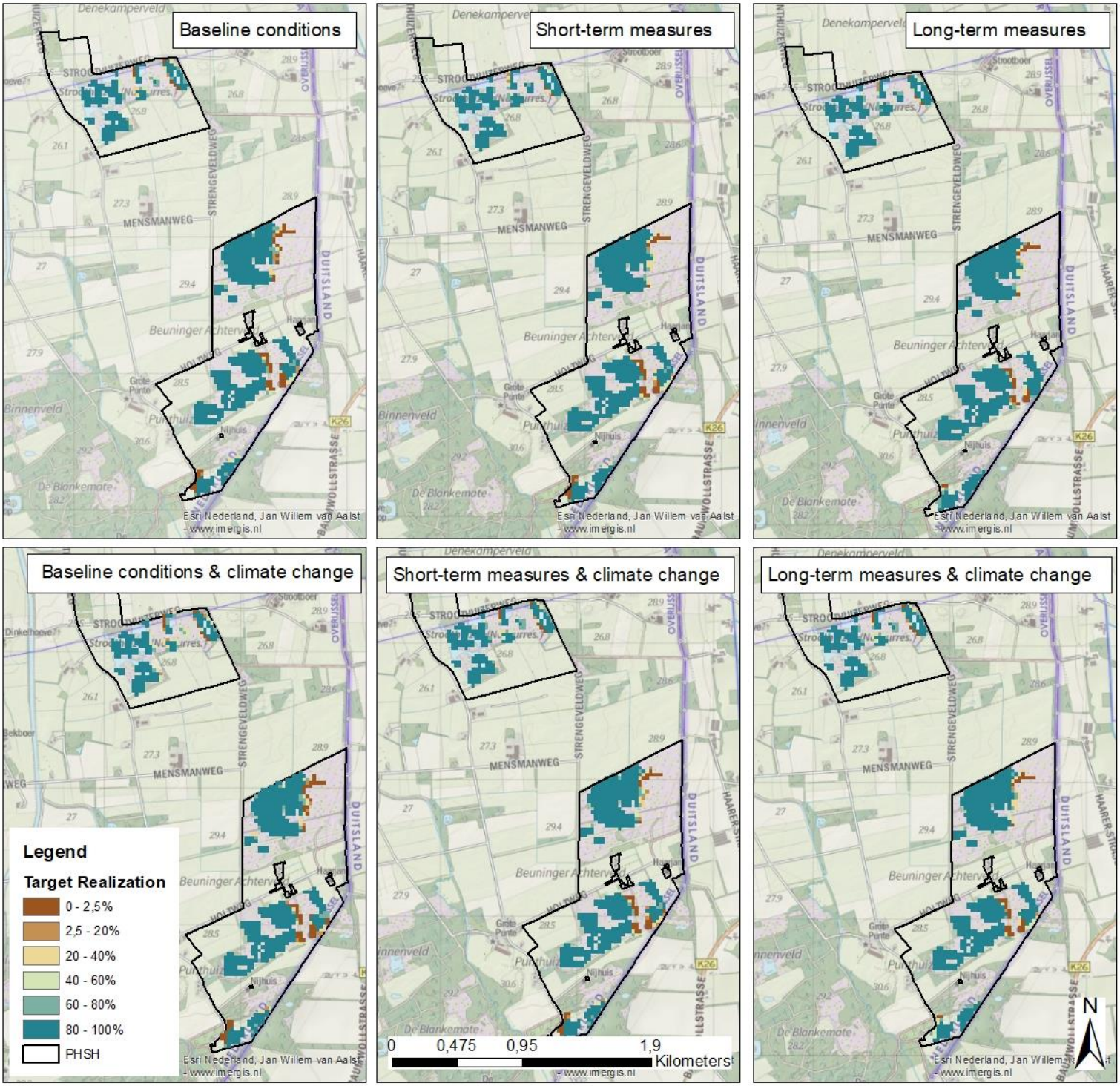
Blauwgrasland - Target Realization Oxygen Stress



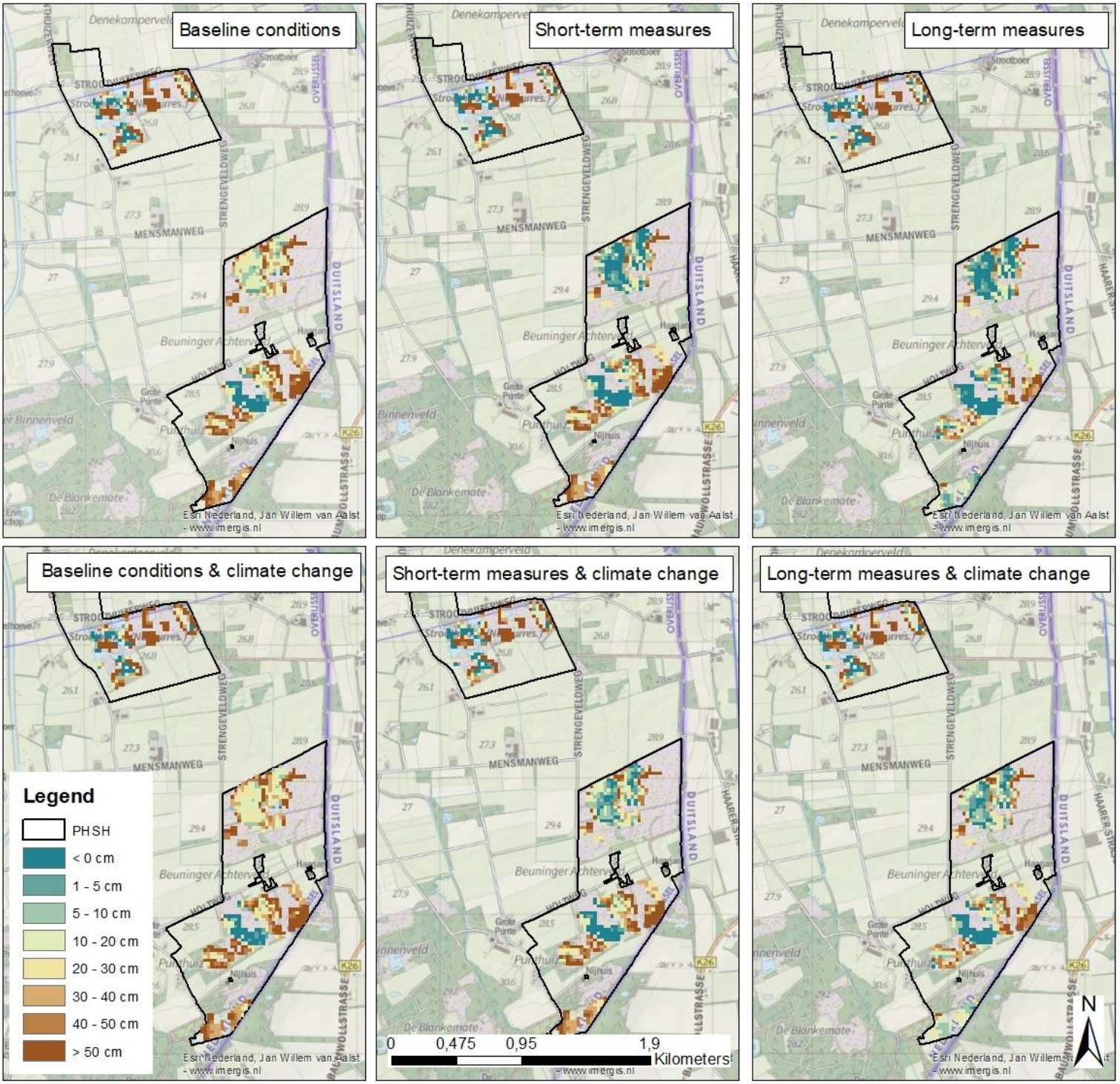
Vochtige heide



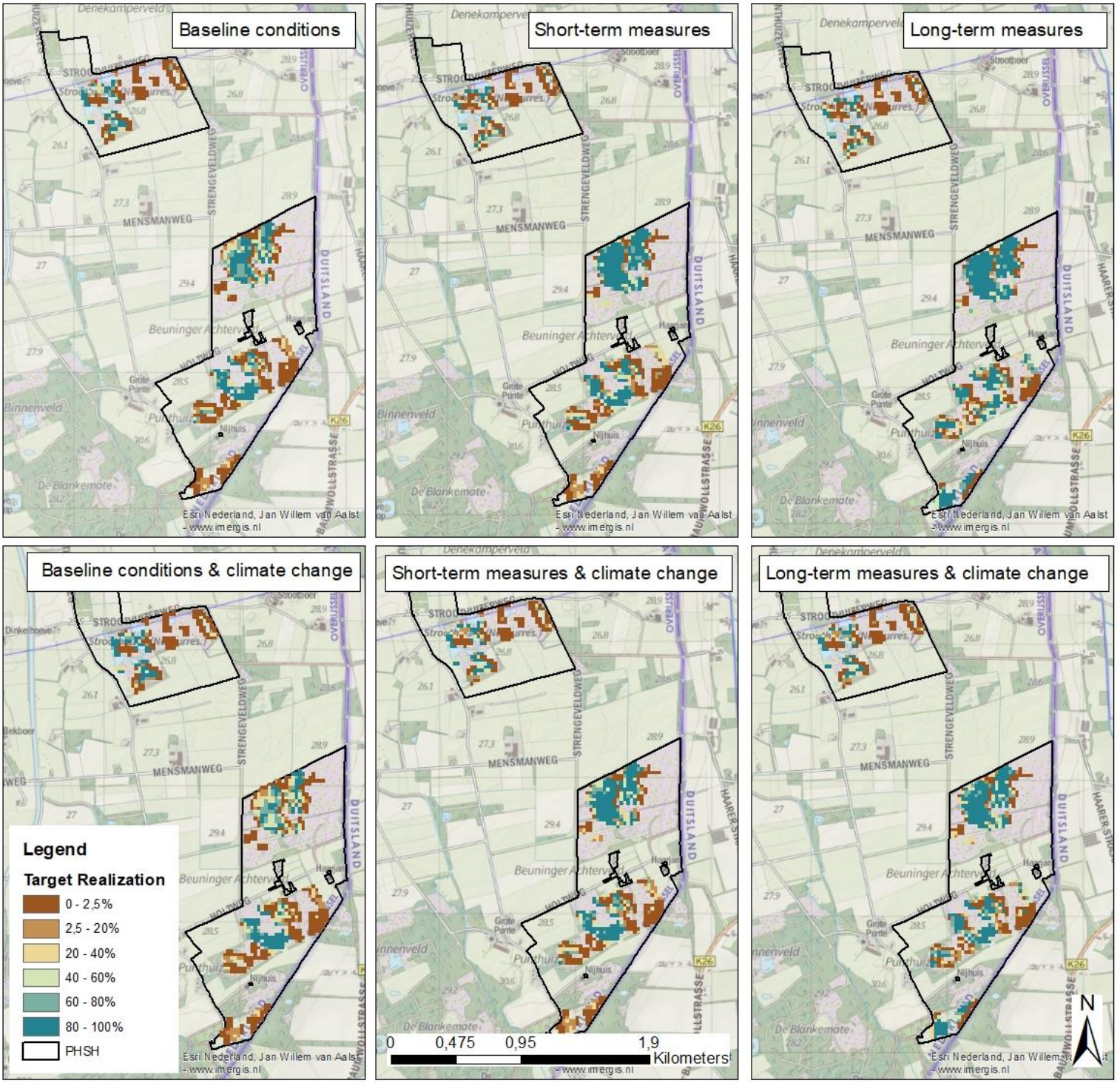
Vochtige Heide - Target Realization Transpiration Stress



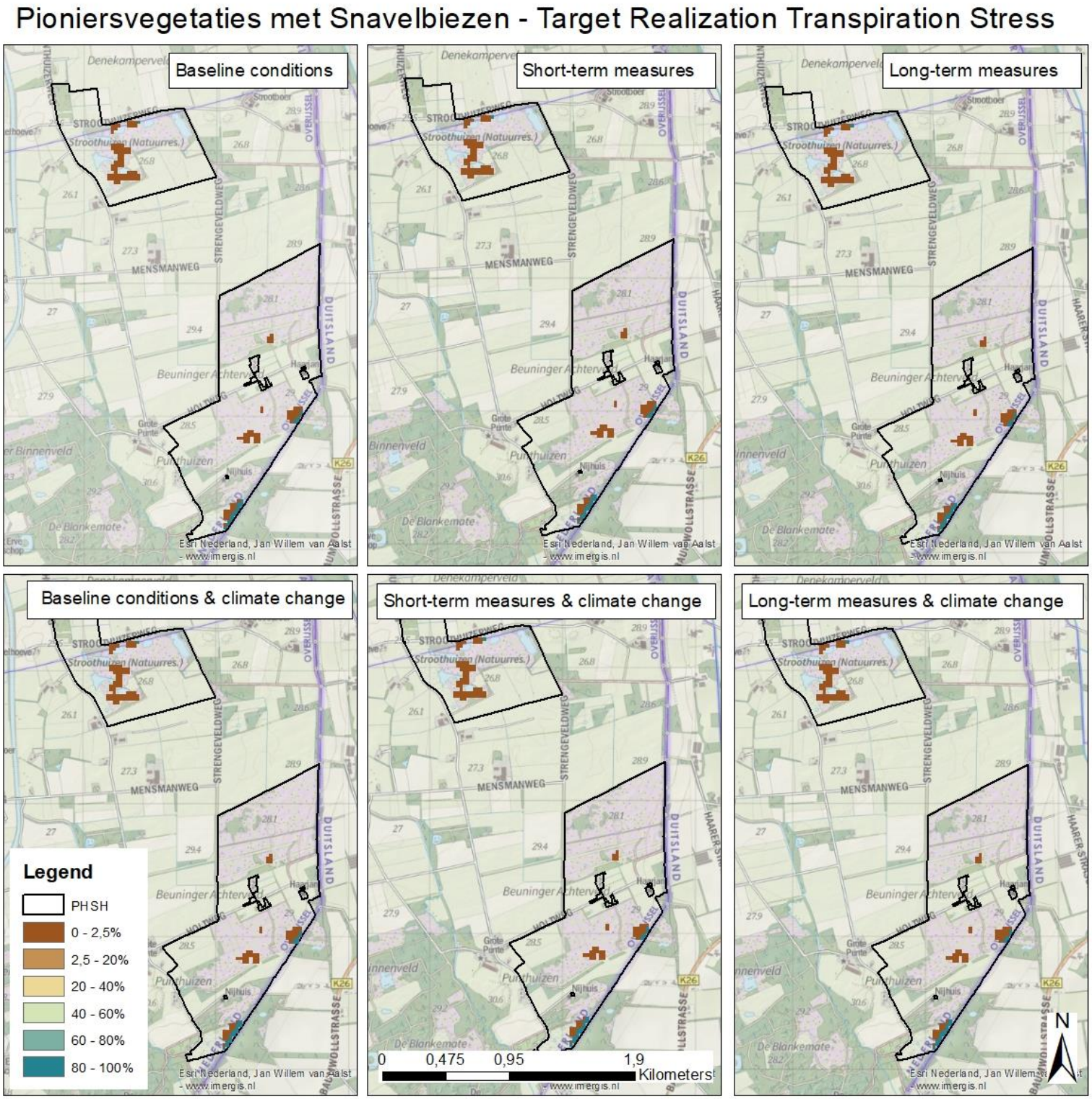
Vochtige Heide - Doelgat GVG



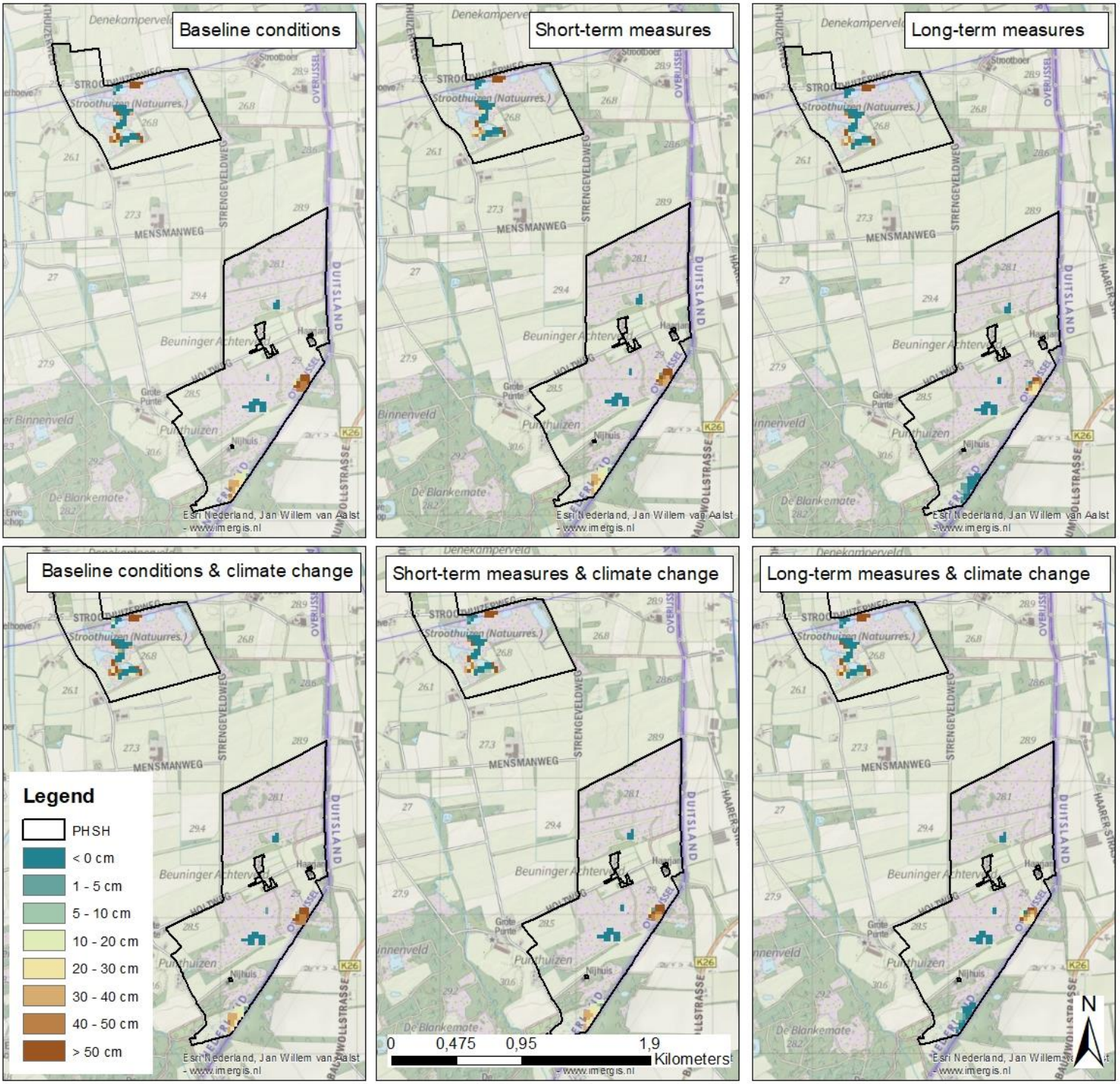
Vochtige Heide - Target Realization Oxygen Stress



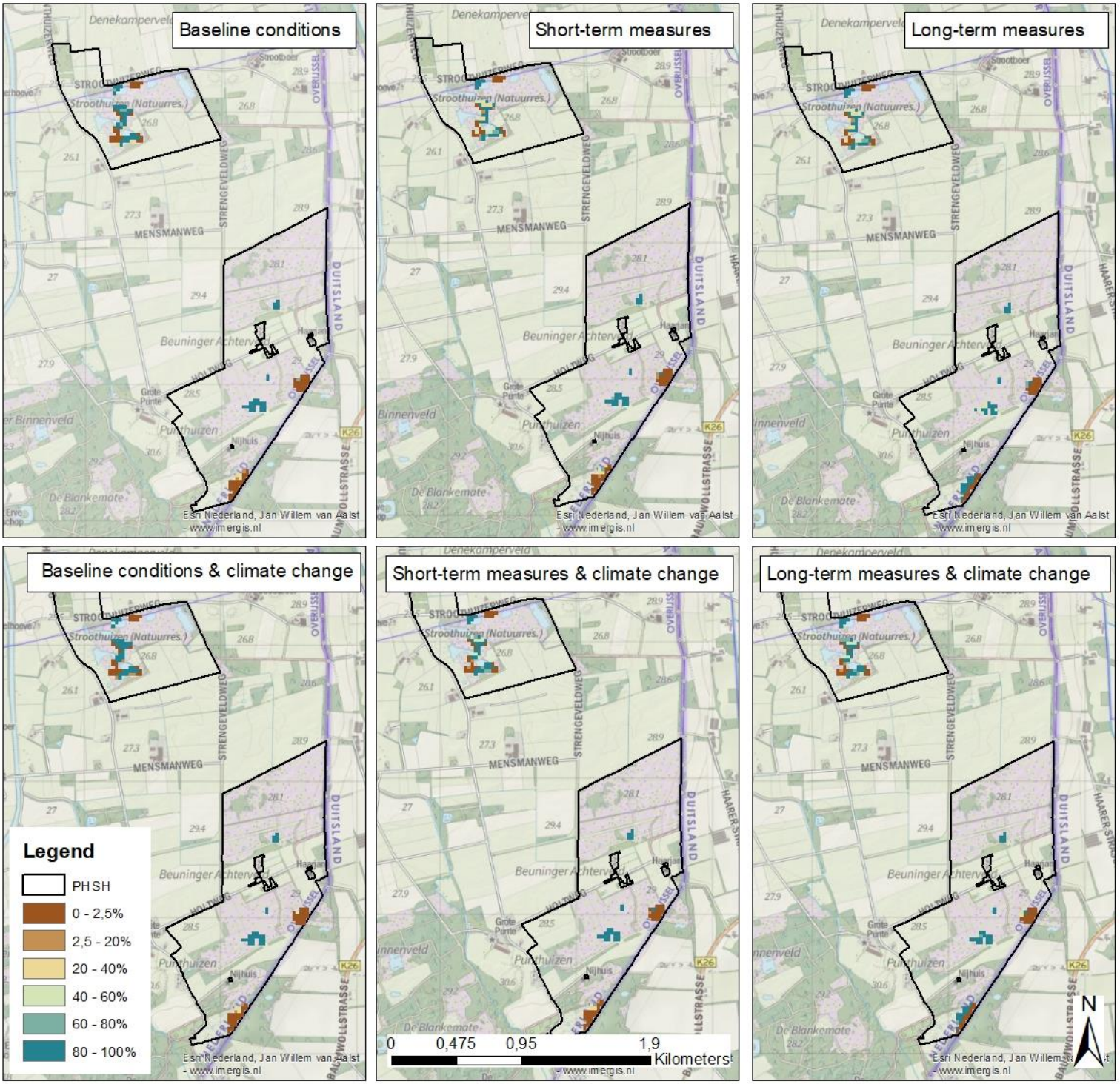
Pioniersvegetaties met Snavelbiezen



Pioniersvegetaties met Snavelbiezen - Doelgat GVG

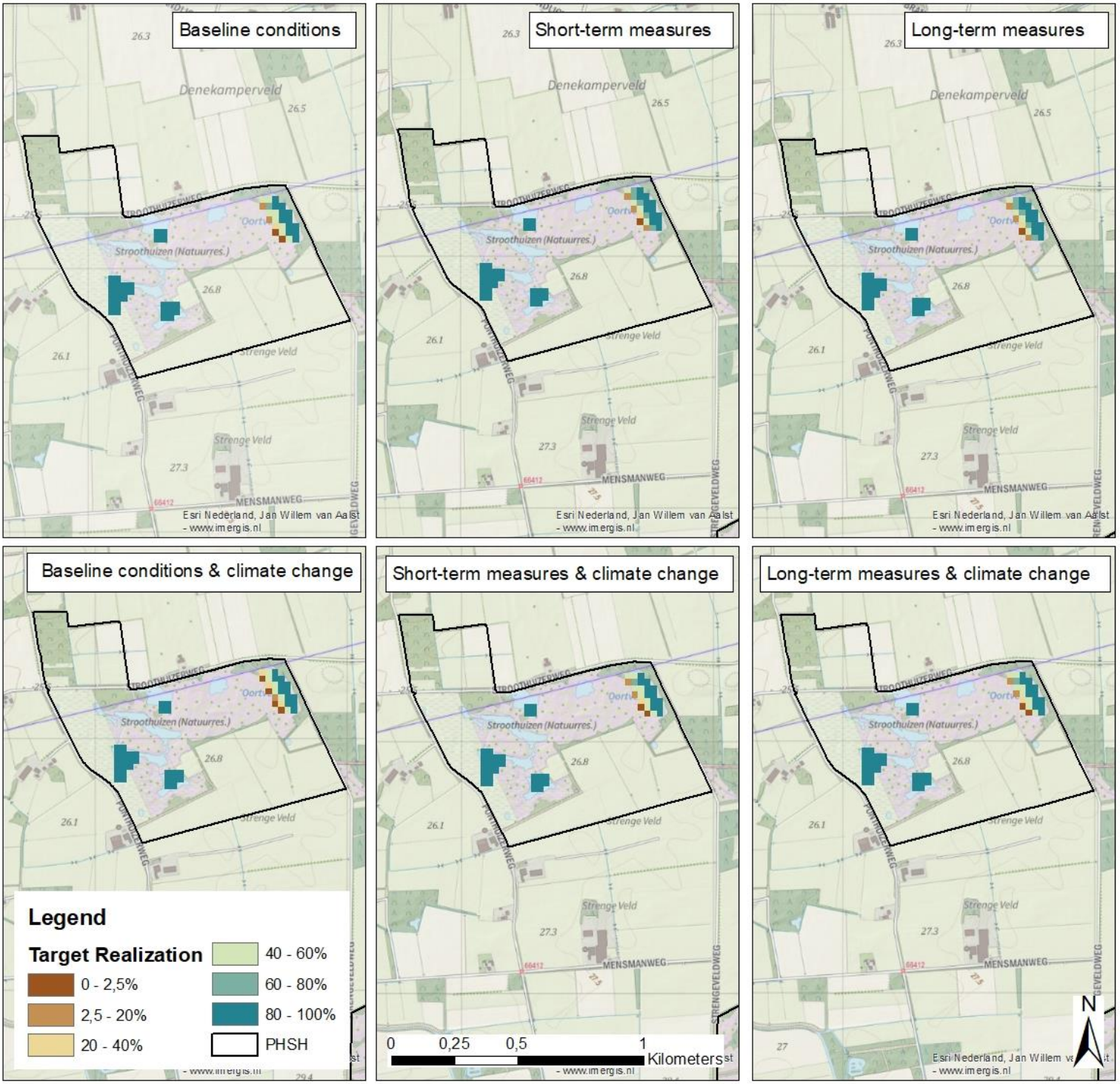


Pioniersvegetaties met Snavelbiezen - Target Realization Oxygen Stress

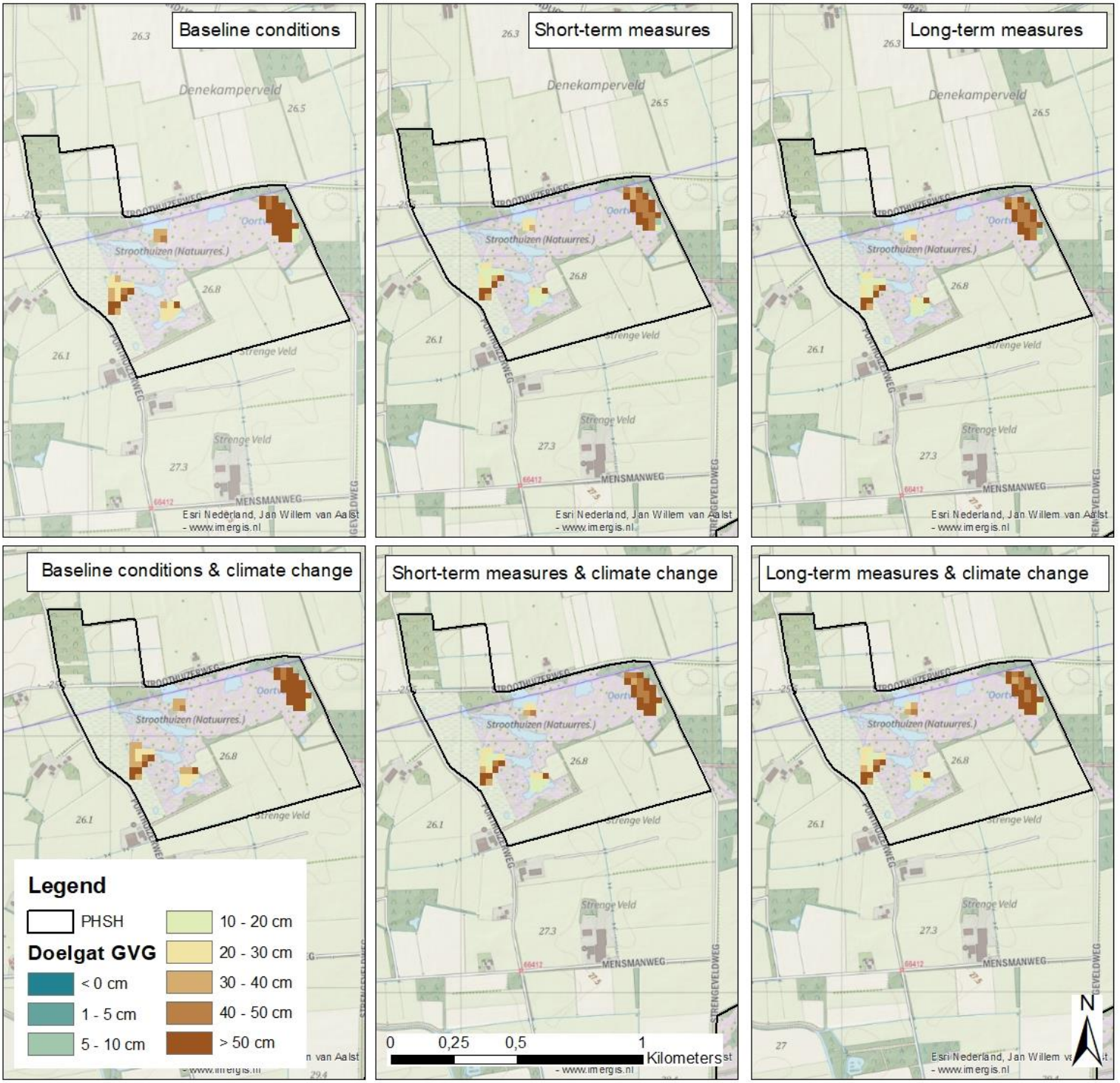


Zwakgebufferde Vennen - Doelgat GLG
Baseline conditions
Short-term measures
Long-term measures
Baseline conditions & climate change
Short-term measures & climate change
Long-term measures & climate change
Legend
PHSH
< 0 cm
1 - 5 cm
5 - 10 cm
10 - 20 cm
20 - 30 cm
30 - 40 cm
40 - 50 cm
> 50 cm
0 0,25 0,5 1 Kilometers
N
Denekamperveld
Stroothuizen (Natuurres.)
Strenge Veld
MENSMANWEG
STROOTHUIZERWEG
Esri Nederland, Jan Willem van Aalst - www.imergis.nl

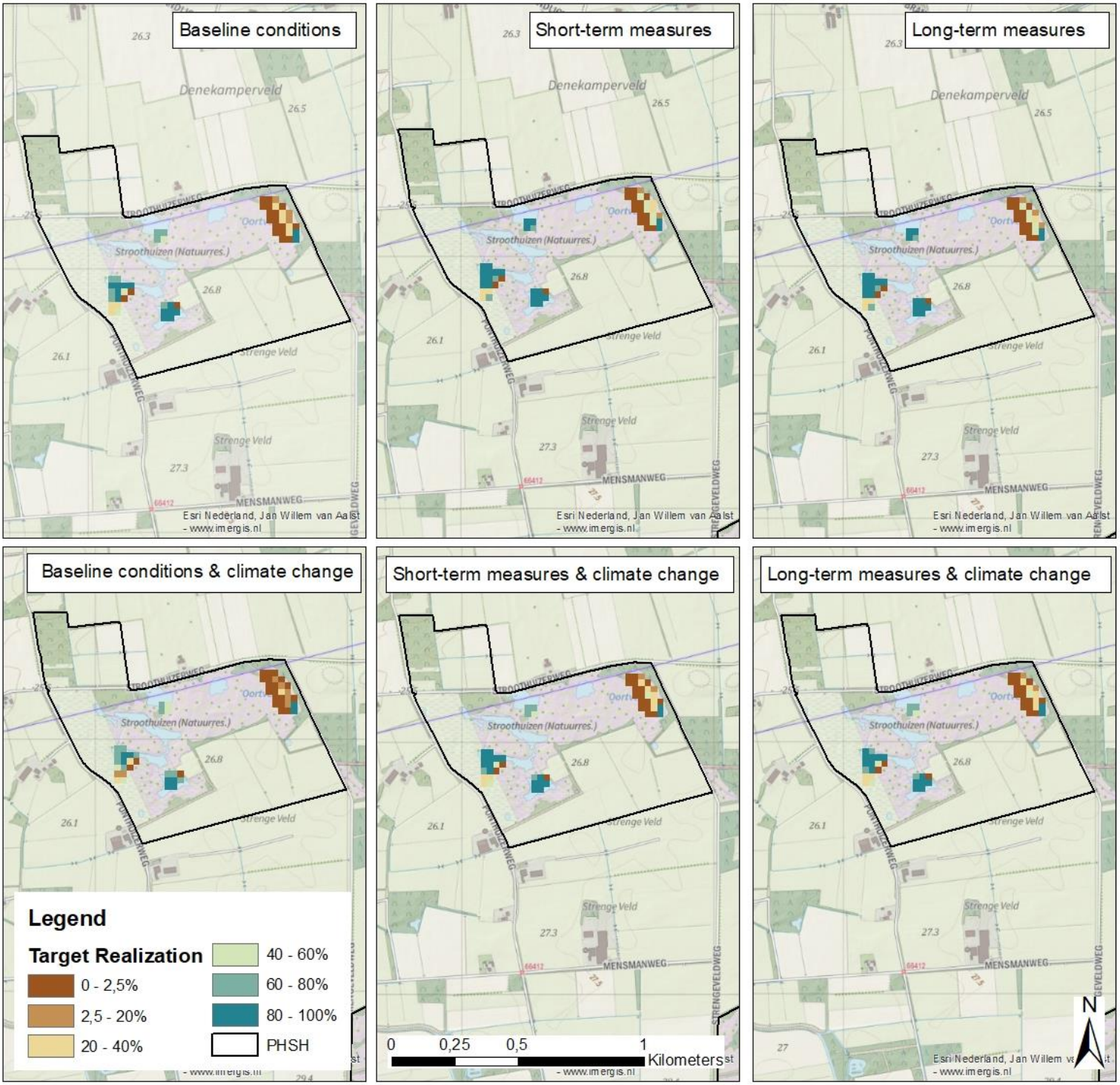
Zwakgebufferde Vennen - Target Realization Transpiration Stress



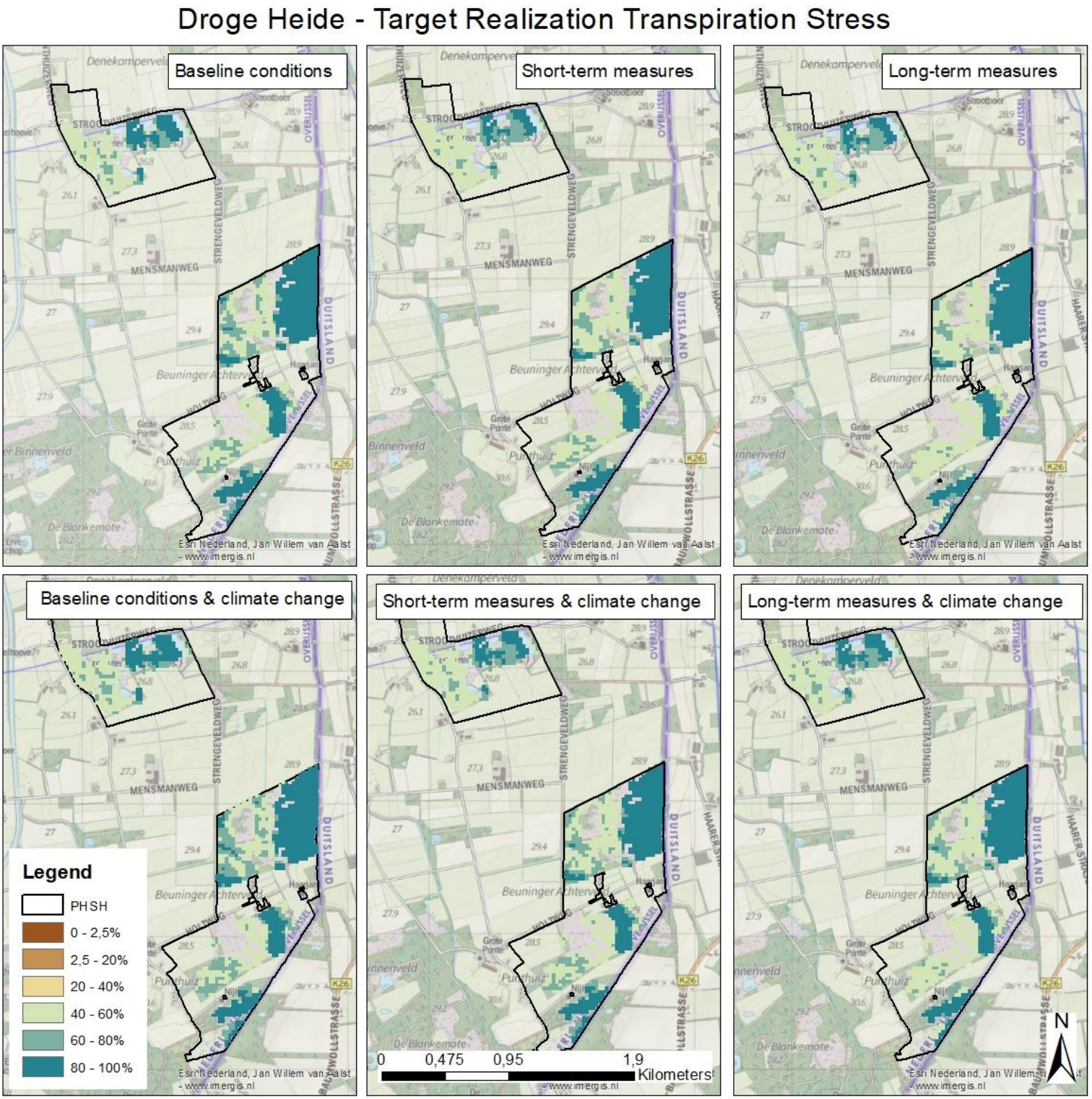
Zwakgebufferde Vennen - Doelgat GVG



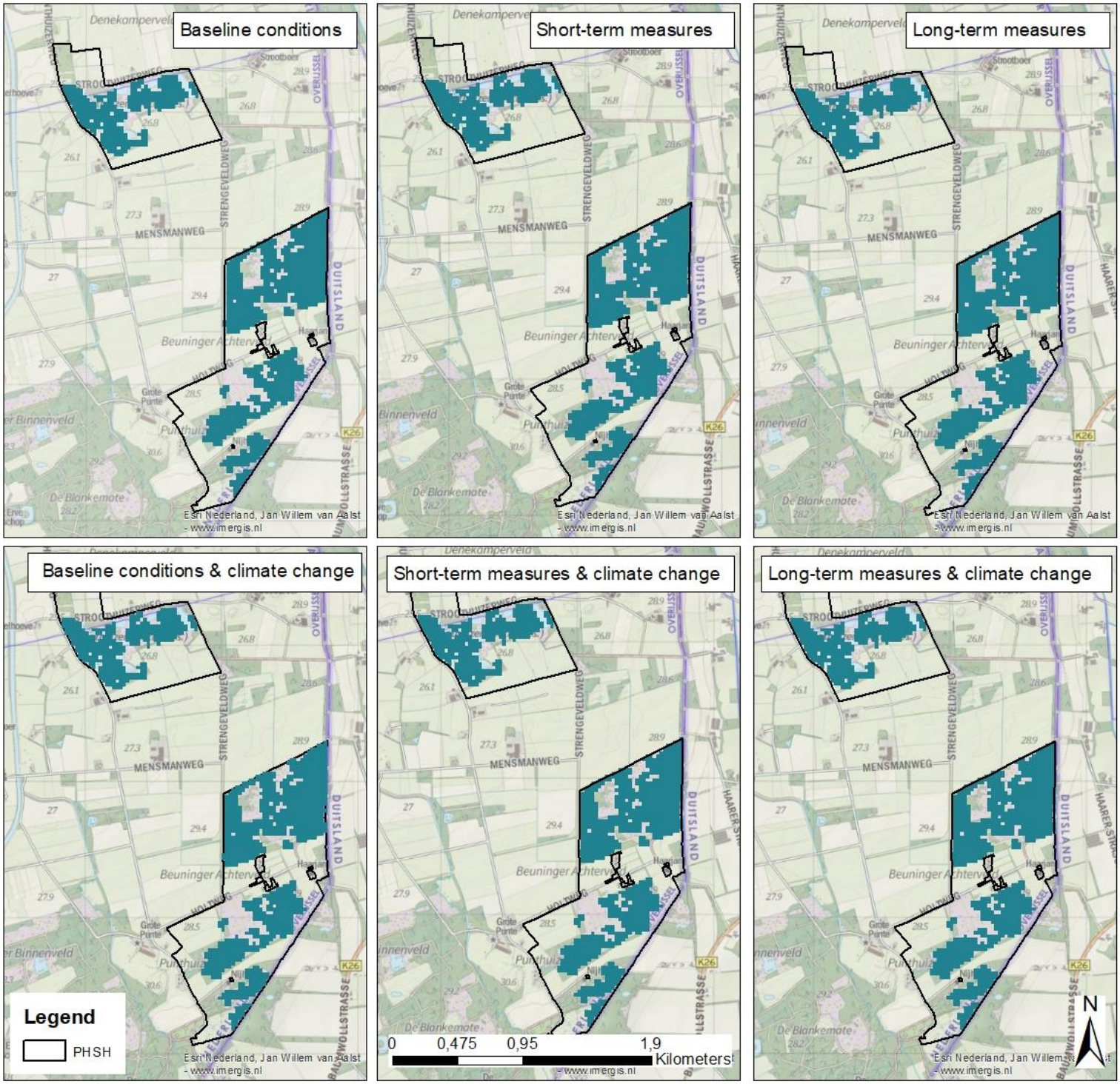
Zwakgebufferde Vennen - Target Realization Oxygen Stress



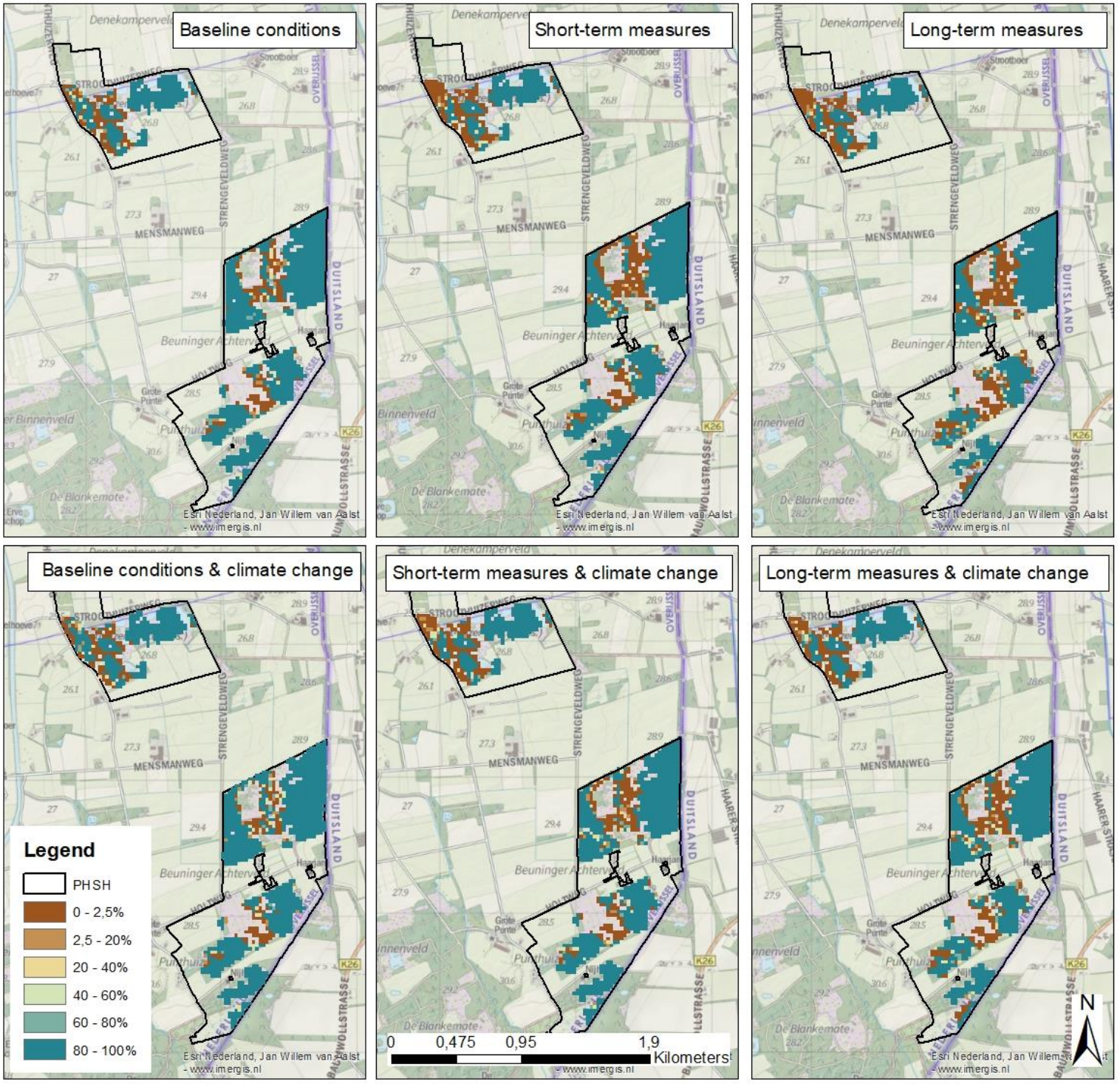
Droge Heide


Droge Heide - Target Realization Transpiration Stress
Baseline conditions
Short-term measures
Long-term measures
Baseline conditions & climate change
Short-term measures & climate change
Long-term measures & climate change
Legend
PHSH
0 - 2,5%
2,5 - 20%
20 - 40%
40 - 60%
60 - 80%
80 - 100%
0 0,475 0,95 1,9
Kilometers
N
Esri Nederland, Jan Willem van Aalst - www.imergis.nl

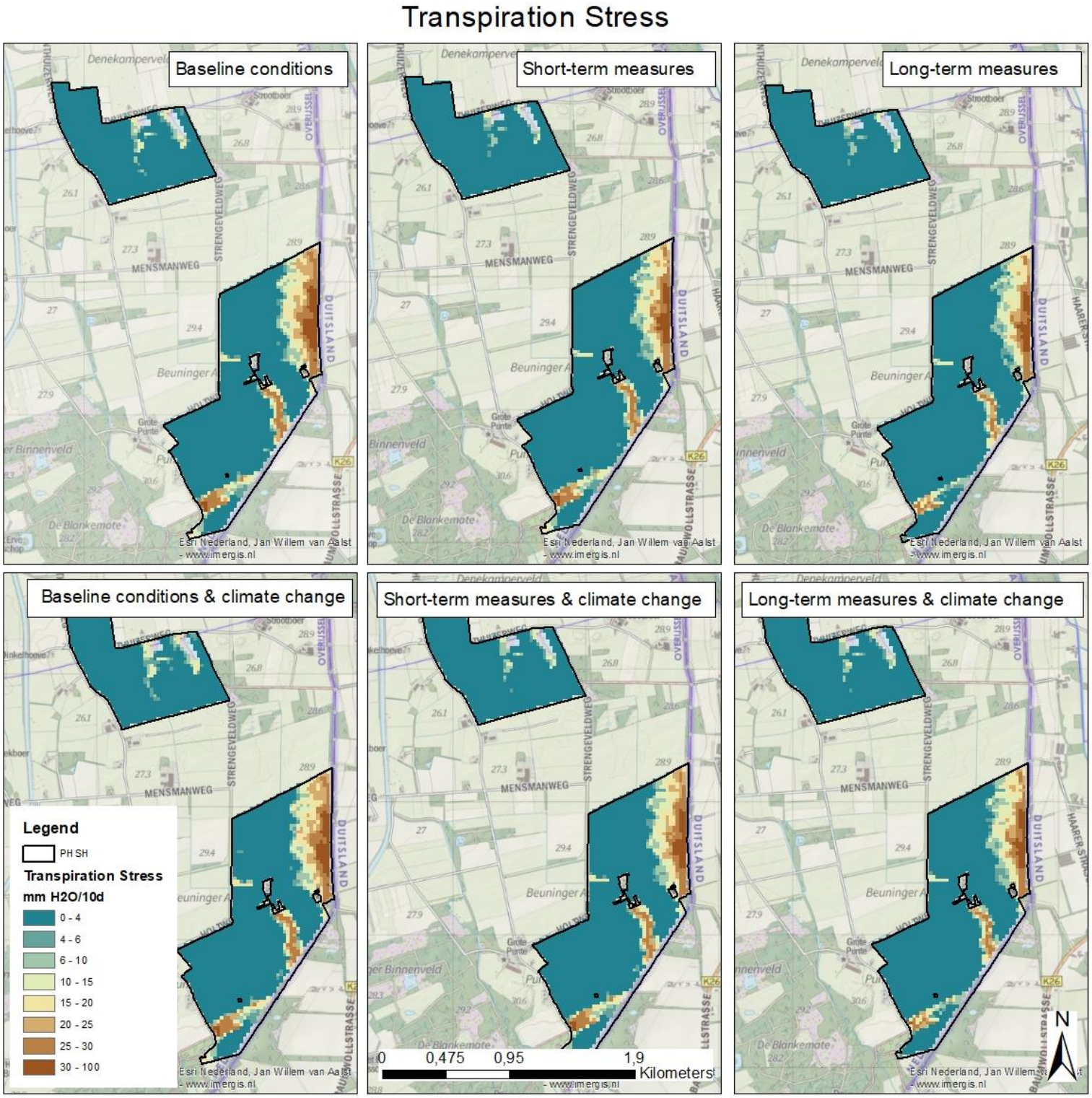
Droge Heide - Doelgat GVG



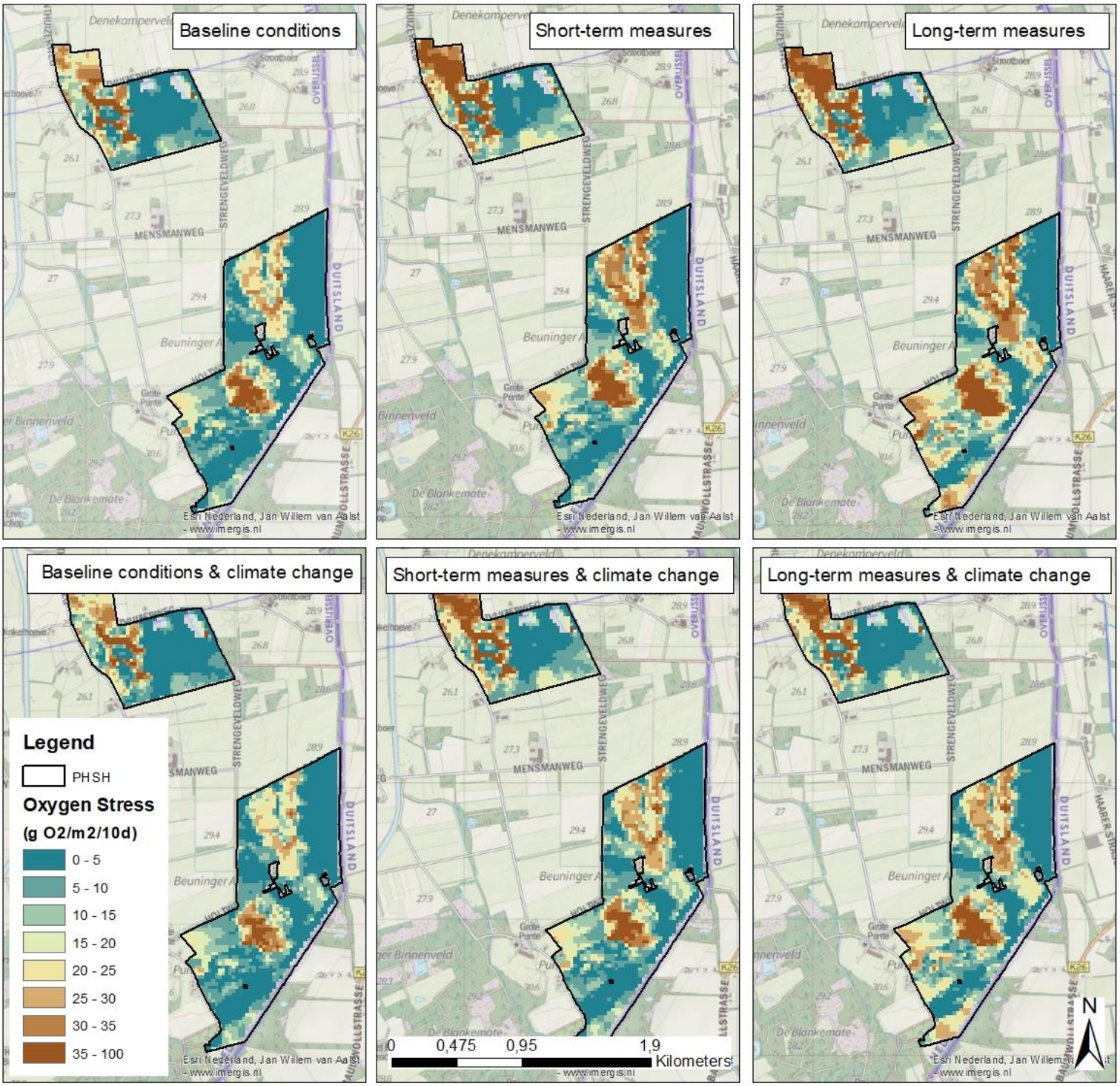
Droge Heide - Target Realization Oxygen Stress



Appendix 7: Transpiration- and Oxygenstress-maps for all scenarios



Oxygen Stress



Appendix 8: Residuals per monitoring well

Monitoring well	Residu GHG	Residu GLG
Punthuizen		
B29C0252	-0.05 tot 0.05 m	-0.05 tot 0.05 m
B29C0245	-0.05 tot 0.05 m	-0.2 tot -0.1 m
B29C0243	-0.2 tot -0.1 m	-0.2 tot -0.1 m
Stroothuizen		
B29A0208	-0.05 tot 0.05 m	No value due to frequently dry well
B29A0204	-0.05 tot 0.05 m	-0.5 tot -0.2 m
B29A0199	0.1 tot 0.2 m	-0.5 tot -0.2 m
B29A0191	-0.05 tot 0.05 m	-0.2 tot -0.1 m