AARHUS UNIVERSITET

Carbon Cycling and Climate Change

The effect of climate change on the hydrological cycle, and its consequences on Danish farmland

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Preface

This report is made by Emad Farzanegan, Maitreya and Emil Dahl in corporation with our supervisor Mathias, and in association with the knowledge and innovation center; SEGES.

The review is highlighted the affection of the climate changes on the hydrological cycle, with a focus on the consequences on the arable land of Denmark.

Abstract

The world is changing rapidly due to anthropogenic GHG emissions. This has significant consequences on the changes of the overall climate, as well as the hydrological cycle. A disturbance in the atmospheric energy budgeting leads to changes in weather patterns. These changes are various in respect to different regions, as they can lead to a drier or a wetter state.

Projections over the northern region of Europe illustrate intensified hydrological activity, suggesting an increase in precipitation, with extreme and frequent events.

The same applies to the climate of Denmark. As the majority of the Danish land cultivated, precipitation patterns' effects on the farmland should be considered, and the possible mitigation tools available to avoid the problems followed by the excessive amounts of water.

In this review, we worked in association with SEGES to highlight the upcoming issue, on both high- and lowland soils, through their current project. When water is removed in upstream areas, downstream sites should be able to handle substantial hydraulic loads to prevent other fields, but also infrastructure, to be waterlogged.

The usage of the models; MIKE SHE and MIKE HYDRO are evaluated with certain advantages and disadvantages in the mitigation of hydrological problems in relation.

Table of content

Hydrological cycle (Maitreya)

Water occupies 71% of the Earth's surface area and it is one of the most important elements for the survival of life on any planet. It also helps in transportation of nutrients in the soil as it is a very good solvent. So, it becomes essential to study about the hydrological cycle. Oceans contain about 96.5% of the total water resources (1.385 billion km^3) present on the Earth (Shiklomanov, Rodda 2003), so most of the water is saline in nature. However, oceans play a major role as a source of water in the atmosphere. Snow covers and glaciers hold about 24.4 million km^3 of water whereas 23.4 million km^3 is present as groundwater, out of which more than 50% is not fresh water (Kundzewicz, 2008).

Water is continuously moving by changing from one phase to another. It is present on the Earth in liquid phase in the form of rainfall, water in lakes, rivers, streams and oceans, as groundwater, etc. It can also be found in gaseous phase in the form of water vapor and in solid phase in the form of ice, glaciers, snowfall, etc. All the phases of water are related to each other and effects on one phase of water can have consequences on the other phase of water.

Together they form the hydrosphere and it is a closed system. Atmosphere, biosphere and lithosphere have an effect on the hydrosphere. In response the hydrosphere influences these three spheres not directly but indirectly. The circulation of hydrosphere is actually under pressure from different environmental factors including climate change mainly due to anthropogenic factors. Since the hydrosphere is in constant cycling and there are many processes like precipitation, condensation, evapotranspiration, sublimation, infiltration, etc. involved in it, so in order to understand the hydrological cycle, let's assume the ocean as the starting point because it constitutes the maximum percentage of water on Earth and evaporation as the initial process although many processes are going on simultaneously.

In terms of volume, the two main processes responsible for transferring the water between the atmosphere and hydrosphere are precipitation and evaporation (Kundzewicz, 2008). So, they are the two important fluxes involved in a huge quantity of water movement. The sun provides the energy in the form of heat that drives the water cycle. Evaporation of water takes place from the ocean and soil moisture due to heat, solid phases of water like ice, snow, etc. directly changes into vapor and water vapor from plants due to transpiration.

Annually, the solar energy evaporates about 500,000km^3 of water, out of which 86% (430,000km^3) is from the oceans and the rest 14% (70,000km^3) is from the land. Approximately 90% of the evaporated water from the ocean precipitates back into the oceans and the rest on the land (Kundzewicz, 2008). Due to air circulation the water in gaseous phase moves upwards and condenses, thus forming clouds. With the help of air currents, circulation of clouds takes place and precipitation occurs in the form of snow, rainfall, etc. This precipitation on land leads to division of water in three parts: overland flow like surface runoff, interland flow like infiltration recharging aquifers and base flow like groundwater. Part of it ultimately reaches the ocean while some is retained on land and the rest evaporates into the atmosphere. The cycle begins again.

From the water layer thickness global water cycle rate can be demonstrated. Evaporation from the oceans results in the conversion of layer of water of thickness 140cm per year into vapor whereas only 127cm per year precipitates back (Kundzewicz, 2008). This means there is a net movement of water from the oceans to the land.

Influence of climate change on Hydrological Cycle (Maitreya)

Solar radiation provides energy for the hydrological cycle. The total incoming solar radiation from the sun does not reach the Earth's surface, part of it is reflected by the atmosphere including clouds, aerosols, etc., part of it reaches the surface, which is reflected by the Earth's surface due to its albedo and the rest of it is absorbed. The greenhouse gases like water vapor, carbon dioxide, methane, nitrous oxide, etc. maintain the Earth's temperature by trapping the radiations from the sun after being reflected by the Earth's surface and making life possible to survive on Earth.

The anthropogenic emissions of greenhouse gases have led to the disruption of the hydrological cycle and climate change. The climate is controlled by the hydrological cycle in various ways. The interchange of heat and moisture between the Earth's surface and atmosphere impacts the thermodynamics and dynamics of the climate setup. In different forms as snow, clouds, vapor, liquid, and ice, and also in transitional states it plays a role in cooling and heating the environment. Evaporation alone contributes to 50% of surface cooling and clouds affect the Earth's radiation budget (Chahine, 1992). Climate change including floods, droughts, precipitation extremes, rising sea levels, heatwaves, etc. is all affected by the hydrological cycle.

Since more trapping of radiation by GHGs will result in higher temperature which means more energy for evaporation and hence cloud formation and more precipitation in the areas which are wet and also extreme weather patterns. But in the dry areas, there will not be enough moisture to evaporate and all the radiation will result in the increase of the temperature making the place drier. The water vapor present in the atmosphere, which strongly depends on a rise in the temperature, increases by about 7% for every 1-degree Celsius rise in the air temperature (Alcamo & Olesen, 2012). Hence, this creates positive feedback in which warming of the atmosphere leads to the higher vapor content and subsequently stronger effect of water vapor on the warming of the atmosphere. This can create situations of run-off, floods, droughts, storms, etc.

Climate change can accelerate the hydrological cycle. The fifth assessment report (AR5) showed that there is a high probability of the hydrological cycle being disrupted by the anthropogenic factors since the 1960s and since the 1970s, there is an increase in global surface air specific humidity (IPCC, 2018). According to AR5, the average precipitation will increase globally with an increase in global warming. Under the RCP8.5 emission scenario, there can be a 50% or more than 50% increase in precipitation in polar and tropical regions whereas in subtropics it can decrease by 30%, by the end of the 21st century (AR5). In the future, there can be a huge difference in annual precipitation between wet and dry areas with wet areas receiving more rainfall than dry areas (AR5). The AR5 reported that though the intensity of precipitation will increase but the frequency will decrease. This indicates the possibility of an increase in runoff or maybe flood in extreme cases in the future but some projections suggest both an increase and decrease in runoff (IPCC, 2018).

The IPCC 2021 suggests that precipitation and runoff will both increase in the northern high latitudes. Abrupt changes in the hydrological cycle like monsoonal circulations and long-term droughts cannot be confirmed and still possess uncertainty. AR6 concluded that due to global warming by anthropogenic factors the intensity and frequency of precipitation have increased globally while an increase in drought events in the Mediterranean region. Since the middle of the 20th century, the glaciers are reducing (Zemp et. Al, 2019) and on average snowpacks have also reduced (Marty et al., 2017). Irrespective of the emission situation, the low elevation snow cover in the high mountain zones are expected to decrease in the future (Beck et al., 2017). Glaciers fed basins and river runoff due to snow is projected to decrease in summer and increase in water by the year 2100 (IPCC, 2021). Globally the evaporation will also increase but by how much it cannot be said certainty as it depends on the projections made by the model and different models project differently (IPCC, 2021). The anthropogenic emissions of aerosols will reduce the precipitation globally and also will disturb the large-scale atmospheric circulation patterns (IPCC, 2021). The land will experience more warming than the oceans (IPCC, 2021). In a wider sense an effect on ecosystems and living beings.

Changes in precipitation due to climate change (Emad)

Global scale

Precipitation happens in response to the expansion of air and condensation of the moisture inside of it in the atmosphere, leading to cloud formations that produce it. Precipitation varies across a range of space–time scales. Generally, global mean precipitation is controlled by the atmosphere energy budget and interactions with cloud formations. Future climate change projections of the water cycle are inseparable from this phenomenon and are much more complex than the projected changes in temperature. With climate change, hydrological activity will either increase or decrease depending on the region, and there are also important local seasonal variabilities in the activity with these changes (IPCC, 2021)

The increase in temperature due to global warming leads to an increase in the water-holding capacity of the atmosphere, leading to a higher hydraulic cycle intensity globally, finally increasing the global mean precipitation (Trenberth, 1998). getting on to the regional aspect, is it important to note out the reason behind the variability of the precipitation, which is simply the travel of moisture within the atmosphere. So, Wet regions are wet because they import moisture from dry regions. Putting this into the context of climate change, it can be concluded that with an increase in temperature, mean evaporation is going to increase, so more moisture is going to travel to the wet regions. This concept brings out the most confident statement towards climate change and hydrological cycle, which points out that the overall pattern of the changes indicates that dry areas become drier, and areas with a high amount of rainfall become wetter (Alcamo and Olesen, 2012)

More precisely, taken from the projections, precipitation amount increases during the current century over high latitudes, just as over currently wet regions in low and midlatitudes more than other areas. This increase Is mainly a response to the increase in frequency and intensity of rainfall events. For example, over the dry regions in the subtropics, the precipitation generally decreases because of decreases in both frequency and intensity (Sun, 2007) these statements are quite noticeable in long term projections, However, in the near term, the trend will not be apparent in all regions owing to natural variability and possible influences of anthropogenic aerosols (IPCC, 2013b) also in small scales, or near precipitation margins, the pattern of the changes are less clear, because of model constraints, and regional circulation shift which are not well understood (Raymond et al., 2009)

Figure 4 illustrates the changes in average precipitation in the observed and long-term projections. In northern Europe, an increase in precipitation in both observed and estimated long-term projections are observed.

European scale

In general, Annual mean temperatures in Europe are likely to increase more than the global mean and this warming is going to be at its largest during the northern Europe winter, as a response, annual precipitation is going to increase with a high chance. In central Europe, this trend is not consistent and the precipitation is likely to decrease during summer. Extremes of daily precipitation are very likely to increase in northern Europe. The largest increases in northern and central Europe are simulated by models in winter. (IPCC, 2013c)

As stated before, local precipitation can be greatly affected by the limitations of moisture availability and circulation systems. Changes in precipitation can also vary substantially on relatively small horizontal scales, especially in complex topography. (Raymond et al., 2009)

In northern and central Europe in winter, where time means precipitation is simulated to increase, high extremes of precipitation are very likely to increase in magnitude and frequency. (Beniston et al., 2007). changes in the frequency of extremes tend to increase with increasing time scale while this is not the case for the magnitude of the extremes (Barnett et al., 2006). However, there is still quantitative uncertainty in the changes in both mean and extreme precipitation.

In the PRUDENCE study done by Frei et al., 2006, eight models projected an increase in mean precipitation in winter in both southern Scandinavia and central Europe, due to both increased wet day frequency and increased mean precipitation for the wet days. In summer, a decrease in the number of wet days led to a decrease in mean precipitation, particularly in central Europe.

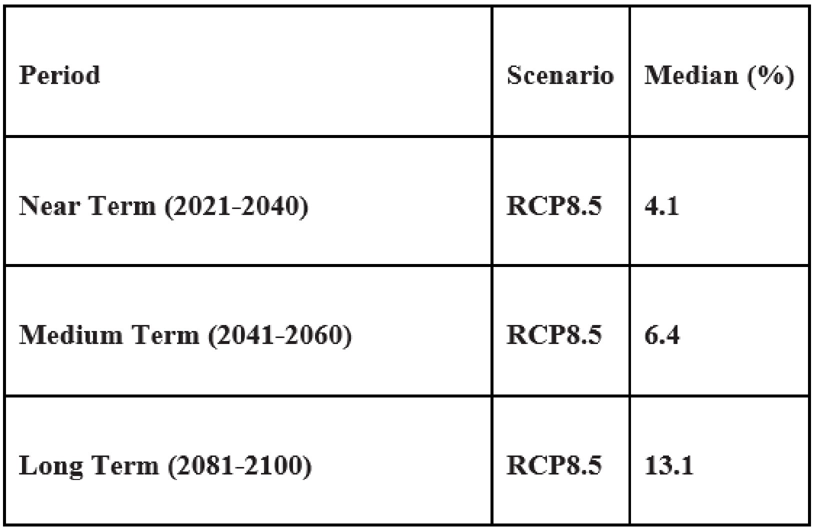
More specifically, The CMIP5 projections reveal an increase in mean precipitation in the winter half-year (October to March) in northern and central Europe. In the summer half-year (April to September), the projected mean precipitation for these regions is going to have a small change. (IPCC, 2013c)

In a recent study by Coppola et al., 2020, projections at a regional scale were made under the EURO-CORDEX, which is a large, high-resolution ensemble, which again shows the north-south dipole, with an increase in the northern part of Europe and decreases in precipitation in the Mediterranean.

Figure 8 illustrates the changes in mean seasonal precipitation in DJF and JJA from this study, alongside the results from CMIP5&6 sub ensembles, for mid-future and far future changes, under RCP 8.5.

Figure 8 reveals that the CMIP6 projection shows the highest values of change. For the summer, over northern Europe, the three ensembles project an increase of about 5% for both the mid-future and far future. But during seasons of DJF, the ensemble shows median changes between 5 and 10 % for those regions in 2041-2070 and higher and more confident changes of 15 to 20 percent for the period of 2071-2100.

The near-term projection over Europe is going to be uncertain because decadal predictability is likely to be critically dependent on the regional impacts of internal climate systems and the variability (IPCC, 2013a). However, in general, the same patterns are observed with less confidence.



Period	Scenario	Median (%)
Near Term (2021-2040)	**RCP8.5**	**4.1**
Medium Term (2041-2060)	**RCP8.5**	**6.4**
Long Term (2081-2100)	**RCP8.5**	**13.1**

Table 1*: CORDEX Europe - Total precipitation (PR) increase % over NEU, Annual (50 models) relative to 1980-2010*

Using the interactive atlas that is provided with IPCC AR6, median values of changes in precipitation over northern Europe in different time terms can be obtained that is included in Table 1.

Overall, a positive change in precipitation in northern Europe is very likely, and with higher frequency and probably higher magnitude in precipitation extremes, future consequences must be accounted for.

Denmark, as a part of northern Europe in this projection, is going to face the challenges of the extra and more frequent precipitation every year, and this can target the agriculture sector through risks of flood, increase in groundwater level and stagnation, failure in existing drainage systems, etc. obeseverd climate data from meteorological stations indicate that there has been an increase of 100mm in average annual precipitation since 1870 (DMI, 2014).

Again, using the interactive IPCC atlas, a rough estimate of the increases in the precipitation can be obtained; 3.5 % median of changes for the 2021-2040 period, 6% for 2041-2060, and 13% for 2081-2100 are the projections estimates as an average throughout Denmark. More prieclsly, DMI in the climate atlas report (2020) stated that projections over denmark show a median increase of 24% in winter precipitation for period of 2071-2100 under scenario of RCP8.5, respective to 1981-2000.

The Climatic and Agricultural scenario in Denmark (Emil)

Denmark is a farming country consisting of 61% farmland, 75% of the cultivated area is used for cereal production for livestock (Danish Agriculture & Food Council, 2019). The water management of crop production is one of the most important aspects, when it comes to growth and potential yield (Legg et al., 1979). Thus, there has been a great deal of interest in optimizing the soil water availability for crop growth. The optimal soil water content lies between the soil capacity and the wilting point of the crop of interest (Lambers et al., 2008). Keller et al., 2012 found a relation between field-saturated hydraulic conductivity and crop yield. The model is based on relative values found in 3 different fields. Here they were able to plot the relative yield as a function of the field-saturated hydraulic conductivity. An optimal yield was observed, indicating that optimal soil should have high enough conductivity to drain excess water, but at the same time the capacity to retain enough water under unsaturated conditions. As illustrated in Figure 2 (Tuller & Or, 2004), the soil water content varies between the different soil types, due to different properties such as texture and carbon content. The combination of a split soil type pattern, from coarse sand in western Jutland to clay soil in the eastern part of Denmark (Adhikari et al., 2013) and a split precipitation pattern (Frich et al., 1997), distributes the soil water content unevenly across the country, causing water management to diversify across the different regions of Denmark.

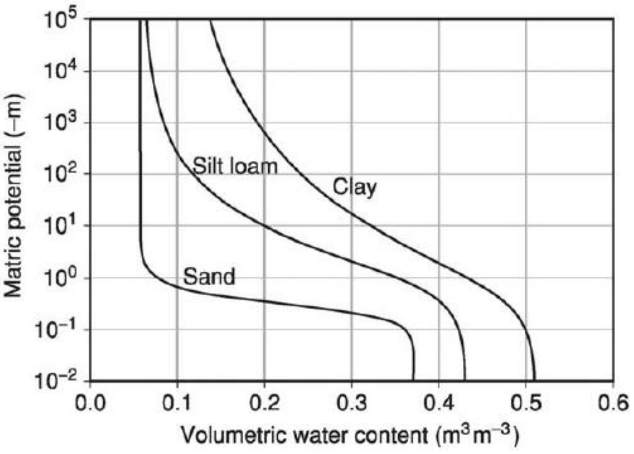


Figure 2: *Typical soil-water characteristic curves for soils of different texture. Source: Tunner & or, 2004.*

The Danish Meteorological Institute (DMI) has predicted the status of the Danish climate at various scenarios, illustrated in Figure 3 in the appendix (Pedersen et al., 2020). The scenarios used in the model are the RCP 4,5 and 8,5, representing different climate outcomes in the future, defined by the IPCC. The different scenarios project more precipitation and more extreme weather, like an increasing number of cloudbursts. The report from DMI suggests that with a CO_2-discharge scenario of RCP 8,5, the temperature will increase by an average of 3,4 °C across the country, meaning that the increasing amount of precipitation that would have fallen as snow, instead will precipitate as rain.

The projection of an increasing amount of precipitation coupled to the water distribution across the country, causes problems with excessive amounts of water in some areas. This provides modelling tools, for projection of groundwater development among other hydrological datasets (Arvidsen et al., 2020). These projections have enabled development of mitigation tools to find solutions to the water balance in Denmark. These models are developed in a project by SEGES[1], to adapt specific mitigation tools to specific situations. Our project group went to a meeting with SEGES for an interview, to get to know more about their project, and the way it is supposed to work out. The project is operating between 3 different target areas: Coast- and running water affected farming areas, waterlogged highland soil and the wetter weather. The goal of the project is to secure valuable agricultural land, which are profitable to cultivate with a financial profit. The project is divided into 5 different working packages concerning everything from mapping and quantification of the flood threatened farming areas and an identification of the causes, to making impact assessments, to which mitigation tools are the best solutions in which scenario. In the end the project should end up with an action plan and a “consequence catalogue”, in which all the stakeholders are able to do a cost benefit analysis to evaluate if an implementation of the given mitigation tool in the given case is profitable in relation to the future forecasts on the given topology (SEGES, 2021).

Various different disadvantages of water-saturated soils can take place if no actions are taking place. The timing of the machine work in the field can be postponed with a risk of late sowing due to the risk of destroying the wet field with the heavy machinery. The delayed sowing date has a significant effect on the crop yield due to the importance of the early crop development (Fathi et al., 2003). In the other end, the harvesting time is important as well. Loss through decreased yield and machinery cleansing accounts for the largest proportions of loss in rapeseeds (Zuo et al., 2014). Also risk of diseases and pests (Anderson et al., 2004; Jones, 2009) and the development of weeds is associated with water-saturated soils.

In our meeting with SEGES we agreed to highlight the importance of drainage in relation to crops' nutrient utilization, as one of the disadvantages mentioned in their project description.

Low nutrient utilization due to poor drainage (Emil)

If field drainage is insufficient various consequential damages regarding the crop may occur. Therefore, having drainage pipes in good condition is a necessity to be able to lower the water table and get rid of the excess water from the agricultural fields (Susgaard Filsø et al., 2018). For instance, a yield reduction of 57% in waterlogged wheat has been observed (Herzog et al., 2016), due to some of the consequences following water stress, such as risk of harmful soil compaction, hypoxia in the rootzone, and poor nutrient utilization. For nutrient uptake to occur, the root has to be in contact with the nutrients in the soil. The nutrients can be taken up by root interception, mass flow and diffusion (Wang et al., 2006). If the field conditions are anoxic, especially in the summer, when soils are quickly exhausted of available oxygen, due to deficient drainage conditions or soil compaction, the root tissue respiration will be inhibited and so will the root development and the nutrient utilization (Patricio Oyarce, 2015).

In terms of decreased nutrient utilization due to poor field drainage, it is important to assess the various pathways in which the nutrients are lost to the environment. The lost nutrients can't contribute to the crop yield, and could furthermore cause environmental problems such as eutrophication. When it comes to nitrogen, the main path of loss in wet conditions is through nitrate leakage, especially surface runoff (Zheng et al., 2019). Due to poorly aerated conditions in water saturated soils, denitrification of ammonia might account for a substantial amount of nitrogen lost in the form of both N_2 and the potent greenhouse gas; N_2O. But the pathway causing the most nitrogen to get lost from the wet fields is nitrate leaching.

In Quemada et al., 2013 a meta-analysis was made to investigate various strategies proven effective in the attempt to lower nitrate leaching on agricultural fields. The reference to show the effect on nitrate leaching was set to be a field with an excessive amount of water, corresponding to a soil compaction or a poor drainage system. Here they compared 82 studies of Improved Water Management, with a mean reduction of nitrate leaching of 58% in relation to the control. The reduction was directly indicated to field management such as reduced tillage, optimization of drain pipe systems etc., implying that a gain in nutrient utilization is to be obtained, when optimizing the water management.

When it comes to the second most important nutrient in crop production; phosphorus, the most important path of loss is through erosion, due to the physicochemical properties of the element and the soil (Sharpley et al., 2001). Soil erosion from an agricultural field can be estimated by the RUSLE-model that predicts the annual soil erosion rate (Krasa et al., 2019). This model includes the rainfall erosivity, soil erodibility, topography of the land and the crop management factor. The rainfall erosivity is expressed as the amount and intensity of rain per area (Panagos et al., 2015). Whereas the soil erodibility determines the soil particles resistance to be detached by water erosion forces (Imani et al., 2014). Because of the forecasts for the precipitation in Denmark, the RUSLE model is influenced in a way that it predicts a larger amount of erosion, and thus a smaller amount of phosphorus available for the crops of interest.

The nutrient utilization is of high importance when it comes to crop production and environmental risk assessment. Therefore, optimization of field drainage, whether it is on- or off field mitigation tools, is of great interest, especially in a future climate perspective.

Mitigation tools (Emil)

In the SEGES project, various mitigation tools are considered in different situations. The main division is between agricultural soils close to streams and groundwater and waterlogged agricultural highland soils, which each have their own properties that make them more suitable for one mitigation tool rather than another.

An agricultural field located close to water bodies has a high risk of being affected by either streams running over the edges or the groundwater table rising from underneath the soil. First of all, the pipe drains should be maintained, so that they have the highest possible water carrying capacities. The maintenance may involve the removal of sedimented soil or replacement of squeezed and destroyed pipes. The capacity is also determined by the slope of the pipe, which typically is designed to have a free discharge to the adjacent stream's mean water level in March. Due to the precipitation forecasts in the future, problems with too high water levels in the streams relative to the drain pipe level, may occur in some areas, and a restructuring of the pipes should be taken into consideration.

By having a higher flow through the streams, it is possible to lower the groundwater table and drain the soil (O'Driscoll et al., 2010), and that principle is used in the mitigation tools of SEGES. The flow through a stream can be approximately described by Poiseuille's law of laminar flow through a horizontal tube: $Q = (P_2 - P_1)/R$, the P's are the pressure at either end of the tube, or stream, and where R is the resistance to flow through the stream. By lowering the resistance, a higher flow would be obtained, resulting in drainage of the surrounding environment. Vegetation cutting in streams is a mitigation tool for lowering the resistance and thereby improving the water-bearing capacity of the stream, resulting in a local decline in the water level and a shift in composition of the plant communities into a more cutting tolerant composition. With the warmer climate and higher CO_2 concentration more vegetation cutting will probably have to be taken into account. The vegetation causes a heterogeneous flow throughout the watercourse profile, leading to different niches with local conditions, providing good circumstances for a high biodiversity. This is a dilemma and a trade-off between an effective water-bearing capacity and good ecological health status, set by the Water Frame Directive and to be achieved by the municipalities (Ministry of Environment, 2007).

Highland soils with problems of waterlogging are characterized differently than the lowland soils, as they are not located close to the permanent groundwater table. They are affected by water either because poor water infiltration or due to a temporarily high groundwater table formed in the winter due to precipitation surplus and bad permeability in the subsoil (Breuning-Madsen et al., 2013), which is going to be an even greater task due to the higher rainfall in the winter as mentioned above. Therefore on-field actions are a big part of the highland soil mitigation strategy in the project of

SEGES. The mitigation strategies are using either mechanically or biological approaches. The impermeability of the soil can be generated in multiple ways, but is accelerated by the mechanical pressure when using heavy farm machinery, which has to be taken into account when loosening the soil through a mechanical strategy.

By leveling the field increasing water infiltration to the soil can be achieved in an efficient way. Leveling reduces local elevations on the field, to give a more even surface and thereby more time for water infiltration. In Hashimi et al., 2018 an investigation on the effect of land leveling on the infiltration ability of the soil was made. The environmental circumstances were in the opposite direction as in the predicted situation of Denmark, with a scarcity of water instead of an excess amount of it. But the target was the same; to optimize the infiltration in the soil. The study showed that the uneven fields were responsible for 30% of the irrigated water losses. Thus, a high potential for water use efficiency is to be gained by land leveling in Afghanistan. The gain is not the same in Denmark, as the country is generally leveled, but some infiltration potential might be possible to gain in local uneven fields, which is also included as a tool in the project of SEGES. Leveling can also be used as a strategy to control the flow pattern. By leveling soil so that the field’s highest point is in the middle of the field, it is possible to allow excess water to run off through ditches in the side of the field as well.

When a field has been processed a lot with heavy machines and tillage with plows, a plow pan in the subsurface of the soil may appear. It’s a layer of compacted soil with a high bulk density and a very low porosity, complicating the infiltration of water. A mechanical approach to infiltrate the hardpan and make the soil more permeable is using subsoiling, where the soil is cut through and not turned around, as when plowing. Zeng et al., 2017 has provided a model to simulate the optimal subsoiling working depth to loosen the hardpan in the most efficient way including depth and time between working sessions.

The biological approach includes root penetration of the hardpan for macropore- and carbon-formation in the soil. In Löfkvist, 2005 a screening between 5 different crops (barley, chicory, lucerne, lupin and red clover), to investigate the different penetration potentials for a better soil structure. They found that chicory and lucerne were the best modifiers, which have beneficial effects in a crop rotation with compaction-damaged soil. Using the idea of incorporating soil organic matter as a strategy for optimizing soil structure is analyzed in Blanco-Canqui & Lal, 2008, where plow tillage was found to accelerate the oxidation of carbon-residues found in the soil, and the no tillage secured a carbon sequestration, leading to a heterogenous soil structure and a lower soil bulk density. In the project of SEGES a combination of a mechanical and a biological approach could be used as a part of the mitigation strategy to form a heterogeneous soil with a high hydraulic transport capacity. After the breakage of the hardpan using subsoiling, an incorporation of roots that don’t have good penetration abilities, might over time create persistent macropores through the hardpan, which can lead away the excess amount of water.

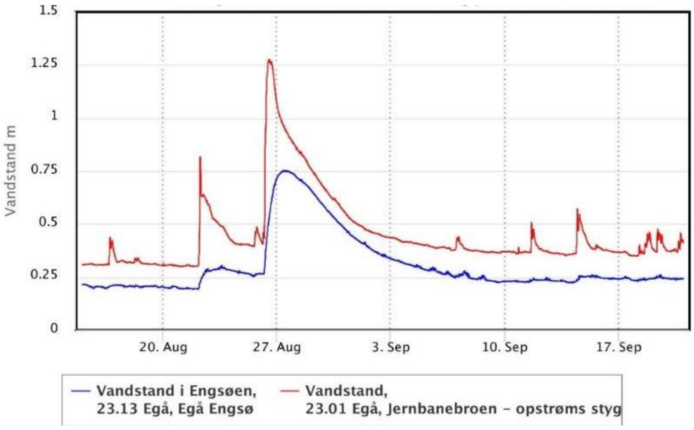


Figure 4: *Water level in the stream input to the lake of Egå, during the precipitation event in August 2012.* *Source: WSP, 2021*

The removal of water from one place might create another problem downstream, and with the forecasts of more precipitation, and more extreme weather, these downstream-sides should be able to handle a substantial hydraulic load. A high hydraulic load in the estuary is not a new issue, and various strategies have been used to create hydraulic sinks in the landscape, and also in the cities. An example is the lake of Egå, which was established by clogging adjacent drains, to prevent eutrophication of the bay of Aarhus. Besides being a denitrifying water body, it also acts as a buffer for hydraulic load to the city of Egå. As illustrated in Figure 4 a heavy precipitation event in August 2012 where 600.000m^3 was stored in the lake (Andersen, 2012). It took 14 days for the water level to return to the normal level, which demonstrates the capacity for a constructed lake to act as a hydraulic buffer in the landscape. Thus, climate lakes and wetlands might as well be considered in the mitigation strategy of the subsequent consequences of getting rid of excess water on fertile agricultural fields.

The effect of the climate changes has a great impact on the hydrological cycle of Denmark, including more precipitation and more extreme weather. SEGES will provide a tool to survey the agricultural challenges, and adapt mitigation strategies for the different situations with different environmental circumstances. These strategies include on- and off-field mitigation tools and downstream handling of the excess hydraulic load.

Adaptation models available (Maitreya)

The Seges used the MIKE SHE model coupled with the MIKE HYDRO river model in their analysis to test different scenarios and effects of mitigation strategies. MIKE SHE is by far the most widely applied physically-based distributed hydrological model that can credibly explain the mechanisms by which ecohydrological processes respond to ecosystem composition organization and composition (Ma et al., 2016). MIKE SHE is an integration of various physically-based models for groundwater flow, unsaturated flow, overland flow, fully dynamic channel flow, their complex interactions and feedback. It also involves processes like irrigation, water quality, snowmelt, and vegetation-based evapotranspiration. There are different modules present in MIKE SHE like irrigation and land use modules which are useful for taking decisions regarding irrigation management and agricultural operations. It also gives the option of editing the models through Python script. MIKE HYDRO river model is the successor of MIKE 11.

It is useful in carrying out flood analyses, investigation of flood alleviation options and tackling hydraulic design within the network of rivers involving canal systems. There are possibilities of improving and changing the model with the help of add-on modules. It also contains the Rainfall-Runoff module which can be used to estimate inflow to reservoirs and rivers and to study runoff impact assessments to perform climate change analyses. MIKE SHE in integration with MIKE

HYDRO river is very helpful in advanced modelling of overland flow, land use change, groundwater and soil water processes. It can integrate different hydrological processes thus an additional benefit of application in various situations. Water dynamics and soil moisture can be more efficiently estimated as it can model for both saturated and unsaturated zones. The user-interface is easy to use. MIKE SHE has certain disadvantages, one being that it is a complicated modelling tool which requires knowledge about hydrology and computers and other being that it requires specific hydraulic properties to model a process.

The SEGES mainly outsource the modelling part to a company which specializes in it because they have hydrologists but do not have engineers in their team. So, SEGES had difficulty in understanding and running the model. Based on the MIKE model they tested five measures. The measures were cleaning up, creating a water park, mini-valley and wetland, and making a double profile and these all were tested in the Gera catchment. It was found and mentioned in their report that no mitigation tool provided complete protection from water logging and groundwater.

Perspectivation (Emad)

As a consequence of climate change affecting the hydrological cycle, extreme weather events leading to a natural hazard will be more frequent; this has been the case for several events in the past decades that the return period was record-breaking.

One of the most recent events induced by the intensified hydrological cycle was the high precipitation and floods in western Europe in the summer of 2021 that led to more than 200 human fatalities and billions of euros in damage to infrastructure. The severe flooding was caused by very heavy rainfall over a period of 1-2 days, wet conditions already before the event, and local hydrological factors.

The observed rainfall amounts in some of the catchments in the flood region broke historically observed rainfall records by large margins. In a study done by world weather attribution, it was found that in the current climate, for a given location within the area of the flood, on average it is expected that one such event happens every 400 years. This means that if a larger extent of western Europe is taken into consideration, and if the climate change effect would play its more intensified role, the return period of such events would be shorter. In the same study, it was observed that Climate change increased the intensity of the maximum 1-day rainfall event in the summer season in this large region by about 3 - 19% compared to a global climate of 1.2 °C cooler than today. The probability of such an event to occur today compared to a 1.2 °C cooler climate has also increased for the 1-day event in the large region (Kreienkamp et al., 2021).

Overall, around 57% of the flooded area in this event was agricultural land (He et al., 2021). Due to this high impact of the arable land, it is expected that the agricultural productivity in western Europe will be drastically reduced. As an extension to the damage done to the agriculture sector, the erosion and sedimentation caused by the flood will lead to soil productivity decrease, as the fertile topsoil washes away.

Conclusion

To conclude, as the intensified hydrological cycle decreased the return period of extreme events even in the current situation, it is expected that northern Europe will experience these unbalanced hydrological extremes, pointing out the need for mitigation and adaptation practices to overcome the incoming environmental issues and loss in agricultural productivity, threatening the wellness and life quality of the modern society. In a Danish perspective, research conducted by SEGES respective to the ongoing and even upcoming environmental abnormalities lead to implementation of large-scale hydrological models on a regional aspect focusing on the low- and highland soils. This is achieved with a trial of balancing the water flow in up and downstream by implementing the outcomes of the adaption tools.

Appendix

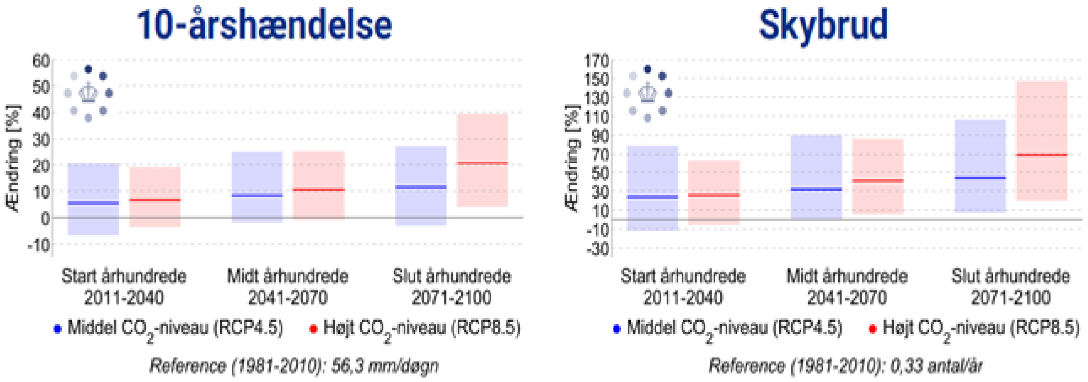


Figure 3: *Percentage change in the precipitation of Denmark in the future periods of: 2011-2040, 2041-2070 and 2071-2100 in the scenarios RCP4.5 and RCP8.5. To the left the 10-year event for daily precipitation, to the right the frequency of cloudbursts. The expected change at the end of the century for RCP8.5 is 21% (4 to 39%) for the 10-year event for daily precipitation, and 70% (20 to 150%) for cloudbursts. Source: DMI, 2020.*

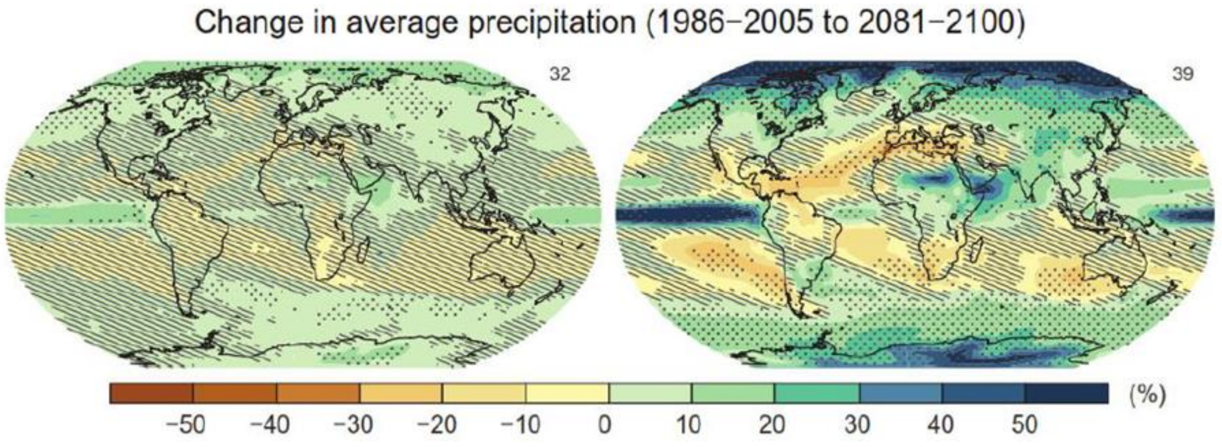


Figure 5: *Multi-model CMIP5 average percentage change in annual mean precipitation (IPCC2013ch12) left rcp2.6 right rcp 8.5*

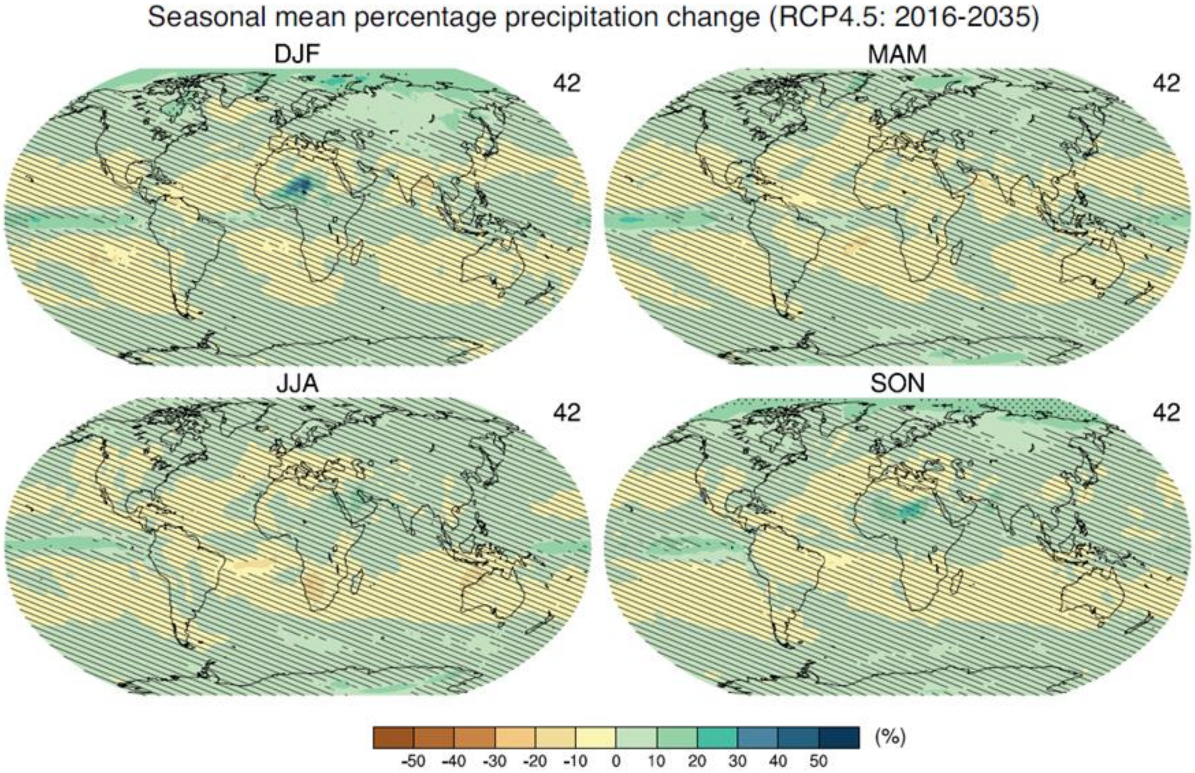


Figure 6: *CMIP5 multi-model ensemble mean of projected changes (%) in precipitation for 2016–2035 relative to 1986–2005 under RCP4.5 for the four seasons.*

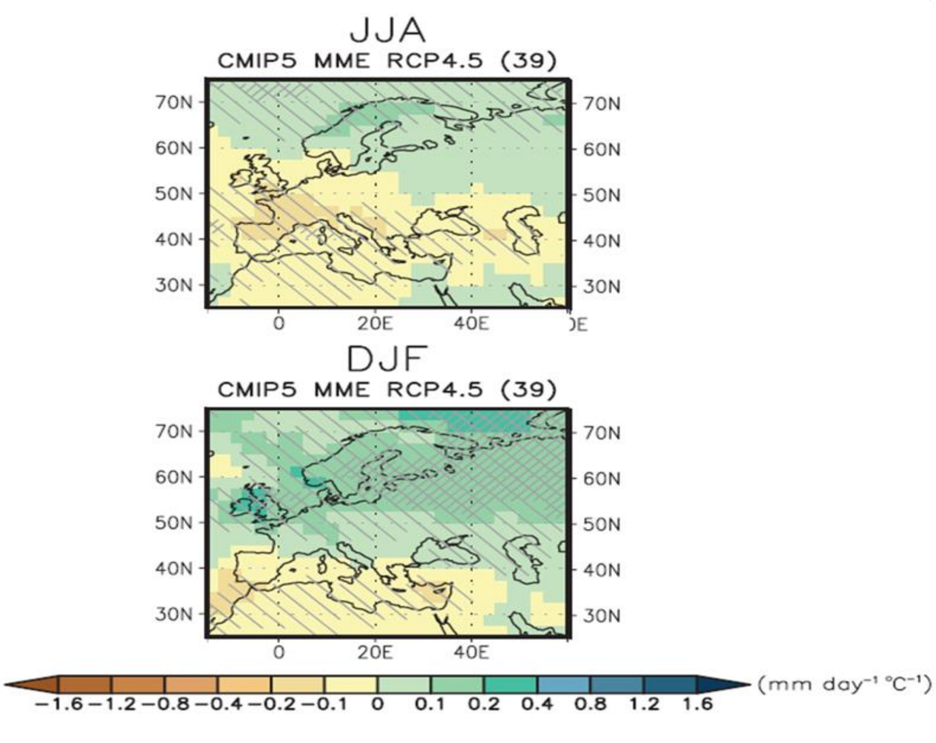


Figure 7: *Precipitation changes for Europe and Mediterranean in 2080–2099 with respect to 1986–2005 in June to August (above) and December to February (below) in the RCP4.5 scenario with 39 CMIP5 models ipccar5 ch14*

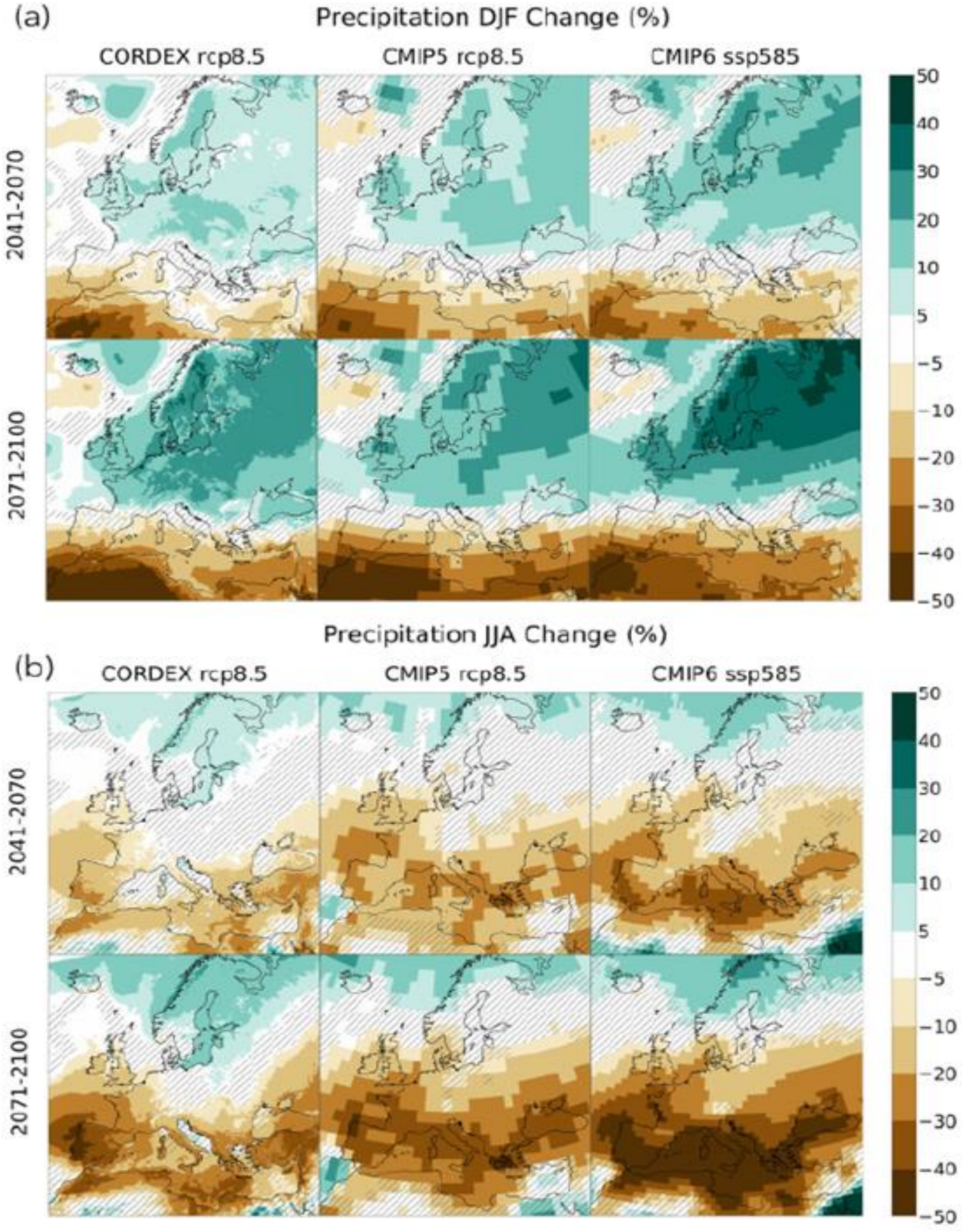


Figure 8: Seasonal precipitation ensemble changes (DJF, a; and JJA, b) (units: percentage). Coppola 2020

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