DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE **RAPPORT 2022/25**

Analysis of drought indicators based on a national coupled hydrological model

Identification of drought events, propagation of drought indices, aggregation level and illustration of how data from HIP realtime model can support vulnerability assessment for damages to houses

Hans Jørgen Henriksen, Raphael J.M. Schneider & Bertel Nilsson

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Analysis of drought indicators based on a national coupled hydrological model

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1. Introduction to the state of the art

There is no operational definition on drought (Hisdal and Tallaksen, 2000), scientists have only agreed on very general or conceptual definitions of a drought, e.g. Beran & Rodier (1985): "*The chief characteristic of a drought is a decrease of water availability in a particular period over a particular area.* Another example (WMO and GWP, 2016). "*A drought impact is an observable loss or change at a specific time because of drought*". Since droughts span a broad set of conceptual meanings or circumstances ranging from meteorological, agricultural, built environment, groundwater to socioeconomic droughts, no single operational definition applies to all circumstances. Therefore policy makers, resource planners, and others have trouble recognizing and planning for drought, and this is why drought planners rely on mathematic indices (anomalies) to decide when to start implementing water conservation or drought response measures.

The year 2018 was the driest year in 99 years in Denmark (DMI, 2018) and an annus horribilis with an epicentre over Central Europa and Scandinavia in terms of agricultural drought and low soil moisture. In Denmark, more than 200 drought-related damages on houses (due to land subsidence) were reported. Maybe 2018 should serve as an early warning about how future hydrological extremes could be a new normal which we have to find ways to tackle. Recent projections of climate change for Northern and Central Europa predicts that drought events will be more frequent and of extended duration in a future warmer climate. This has been evaluated for both consecutive meteorological summer droughts and long-duration hydrological droughts for Rhine basin (Wiel et al., 2022). Drought projections for Skjern å catchment that included drought indicators for soil moisture and streamflow drought by Chan et al. (2021) show that future climate conditions would result in increased risks of drought throughout the study area towards the end of the century, in terms of both intensity and frequency. Until now there was no insurance coverage for buildings affected by drought like for other hydrometeorological hazards. As a response to this extreme drought event, the Danish Parliament decided on a new law where drought damages on houses was incorporated among storm surges and flooding damages from rivers and lakes, as a new risk management task of the Natural Hazards Council (former Stormrådet). From 1 July 2022, this council manages the law on drought damage for buildings if they are caused by prolonged drought in the subsoil.

Drought damages are not only a question of a low groundwater level or low moisture content in the unsaturated zone. Vulnerability and exposure of houses also depends on geology where especially deposits with specific clay minerals are in focus as a specific risk factor. Therefore, The Geological Survey of Denmark and Greenland (GEUS) has made a first evaluation of possible drought indices and vulnerability factors related to the geological setting, clay content and mineralogy in the topsoil and the subsurface layers, relevant for a better understanding of drought hazard maps and drought damages on buildings. GEUS operates a national water resource model which delivers model results on a daily basis to a national portal (Hydrologic Information and Prediction System – HIP), which provides a nationwide integrated dataset ideal for describing soil moisture and hydrological drought effects (https://hip.dataforsyningen.dk/).

The increase in temperature, because of climate change, also affects annual precipitation and evapotranspiration in Denmark under high (RCP8.5) and intermediate (RCP4.5) emission scenarios as described by HIP (Henriksen et al. 2020), resulting in more frequent soil moisture and hydrological droughts in Denmark in the future (Chan et al., 2021). Although the direction and magnitude of the monthly changes in precipitation and temperature is not the same for all climate models, they all agree on higher precipitation during winter and higher evapotranspiration during summer. These patterns of changes in winter precipitation and summer evapotranspiration and the impacts on hydrology and groundwater corresponds well with previous climate change studies for Denmark (e.g. Karlsson et al., 2016, 2015; Seaby et al., 2013).

Water stress, e.g., insufficient quantities of water to cover different services (abstraction of groundwater for industry, agriculture, households and nature, a sufficient high soil moisture and groundwater level during extreme events, etc.) are observed in Denmark in dry years because of meteorological, agricultural and/or hydrological droughts (see definition below). Different concerns have been raised, e.g., in relation to infrastructure (deep foundation, CISA 2021) or saltwater intrusion (EPA 2022). However, drought impacts on building foundations placed in plastic clays have to our knowledge not yet been described in the scientific literature for Denmark.

It is well established that water scarcity can be aggravated by (1) poor water management, with inadequate water allocation in time and space, (2) increased demand for urban, touristic, industrial, and agricultural uses, and (3) pollution with reduced availability of sufficient groundwater with a good water quality. A distinction is normally made between different times/durations of the events and distinctions are made between meteorological (precipitation departure from normal over some time), agricultural (needed soil moisture of a particular crop at a particular time), and hydrological (usual expressions of deficiencies in surface and subsurface water supplies) droughts. Hydrological droughts thus reflect effects and impacts of meteorological drought on groundwater level, river discharge, and ecosystem services. All types of droughts either meteorological, agricultural and/or hydrological droughts are linked to the wider socio-economic and institutional / adaptation aspects of environmental management (associating droughts with the supply of and demand for economic goods). This leads towards the current drawbacks in drought risk management and water security policies, where crisis management merely aims to reduce (or compensate) the damage resulting from drought impacts. Ideally, risk-based management more effectively prevents drought damages by reducing vulnerability to drought (e.g. houses constructed in a way that would be less vulnerable to low soil moisture or groundwater level).

1.1 Drought indices

In a handbook on drought indicators and indices (WMO and GWP 2016) described *drought hazards* as something which can be characterized in terms of their severity, location, duration, and timing. They defined a drought impact as an observable loss or change at a specific time because of drought. The handbook defined *indicators* as variables or parameters used to describe drought conditions (precipitation, temperature, streamflow, groundwater, reservoir levels, soil moisture and snowpack). *Drought indices* were computed numerical representations of drought severity, assessed using climatic or hydrometeorological inputs, i.e. based on drought indicators and calculated ‘anomalies’. A distinction was made between (i) using a single indicator or index, (ii) using multiple indicators or indices, and (iii) using composite or hybrid indicators. Indicators were categorized in the handbook by type and ease of use and grouped into the following classifications: (a) meteorology, (b) soil moisture, (c) hydrology, (d) remote sensing, and (e) composite or modelled.

Hisdal and Tallaksen (2000) described several complex drought indices that have been developed, of which one of the most frequently applied is the Palmer Drought Severity Index, PDSI (Palmer, 1965). Other multivariable indices are e.g. the Surface Water Supply Index, SWSI (Shafer & Dezman, 1982), the Standardized Precipitation Index, SPI (McKee et al., 1993), and the Crop Moisture Index, CMI (Palmer, 1968).

For meteorological drought, the standardized precipitation index (SPI) was highlighted by WMO as a starting point for meteorological drought monitoring (precipitation as input) and is easy to use. Crop moisture index (CMI) was another commonly used indicator, with precipitation and temperature as inputs, and with weekly values required. An alternative to this was the drought reconnaissance index (DRI) which required monthly data on precipitation and temperature. The Palmer drought severity index (PDSI) required serially complete data and inputs from precipitation, temperature, and available water content.

The Soil Moisture Deficit Index (SMDI) was developed from research at the Texas Agricultural Experiment Station, United States, by Narasimhan and Srinivasan in 2005. Characteristics: A weekly soil moisture product calculated at different soil depths, including the total soil column, at 0.61, 1.23, and 1.83 m. This index could be used as an indicator of short-term drought, especially using the results from the uppermost 0.61 m layer. As input parameters, modelled data from a hydrologic model was used to compute soil water in the root zone every week (originally developed for SWAT model). SMDI was useful for identifying and monitoring drought affecting agriculture.

The WMO/GWP handbook did not describe any groundwater indices. A survey of drought indices (WMO & GWP, 2016) used in different countries did not mention any water scarcity or drought indicators used in Denmark. But even though drought or water scarcity seems to be a new challenge as part of climate change adaptation in a Danish context, there has been a few studies with focus on drought in Danish cases. In the next session we will come back to few of these.

1.2 From soil moisture and groundwater drought indices to multifaceted and holistic drought indicators

Tijdeman et al. (2022) described a holistic spatiotemporal, large-scale to local-scale drought monitoring approach for evaluating the multifaceted impact of drought applicable for central and northern Europa. In this prospect the authors advocated for the importance of short- and long-term drought management to better cope with the drought events, as well as to be better prepared for future drought episodes. Key here was an analysis of past droughts at different scales using the historical period 1990-2019, similar to the HIP historical 30-year period - see Henriksen et al. (2020). The applied approach had two main objectives: (1) Locally relevant drought management benefitting from detailed information that considers different hydrometeorological variables and drought-related impacts and their spatiotemporal variability (Van

Lanen et al. 2016) and (2) Drought information in a more generalized form, e.g. indexed information aggregated to administrative regions indicating whether there is drought or not. The latter simplified the interpretation but came at the cost of loss of information as the hazard and its impacts sometimes were highly variable in space and time (Stahl et al. 2016). Contrary to the methods described by WMO and GWP (2016), where drought was defined as a below normal hydrometeorological anomaly (meteorological, agricultural, hydrological or socio-economic), the holistic approach by Tijdeman et al. (2022) focused on an understanding of drought which was multifaceted.

The aim of the multifaceted approach underlined the importance of a drought understanding where co-occurrence in different domains worsen drought impacts, e.g., agricultural drought impacts caused by low soil moisture can be aggravated by co-occurring hydrological streamflow or groundwater level droughts that limit or prohibit withdrawals of surface or groundwater water for irrigation (Tijdemann et al. 2022) in such extreme dry situations.

Chan et al. (2021) conducted a study for Denmark, evaluating SMDI (soil moisture deficit index), together with the standardized groundwater depth index (SGDI) and streamflow drought index (SDI) for the Skjern å Ahlergaarde catchment. Included was the use of the projections from an ensemble of 16 regional climate models downscaled and bias-corrected to 10x10 km for 1990-2100 for a high (AR5 RCP8.5) climate change emission scenario (Pasten-Zapata et al. 2019) as inputs to a MIKE SHE catchment model. The key findings of this work were that all three drought indices agreed that future climate conditions would result in increased risks of drought throughout the study area towards the end of the century, in terms of both intensity and frequency. According to the calculated values of SMDI, SGDI, and SDI in the future climate, the number of extremely dry weeks in the future period accounted for 1.2 %, 4.6 %, and 5.8 % of the weeks, respectively, which is more than twice the figures for the historical reference period. Altogether, the root zone of the study area was expected to be drier during summertime under RCP8.5, implying that the Ahlergaarde catchment faced greater threats from extreme drought and related hazards (e.g., crop productivity reduction and water scarcity) in the future than for the historical reference period.

1.3 Objectives of this technical report

The purpose of this technical report is:

(1) to identify drought events in the period January 1990 - August 2022 based on results from the historical HIP dataset based on the 100 m DK-model, and investigate how these episodes can be grouped into different types with similar hazard characteristics and impacts (focus will be on the periods 1992-1997 (last multi-year drought in Denmark) and 2018-2019 (last severe summer drought in Denmark)

(2) to evaluate the propagation of drought events (meteorological, agricultural, and hydrological drought) with the incorporation of drought indices from Chan et al. (2021) for soil moisture, streamflow, and depth to shallow and deep groundwater; and

(3) to briefly discuss results and aggregation level (spatial and temporal) in relation to HIP portal datamodel

(4) to illustrate how data from the HIP model (real-time) in near future can support societal resilience and vulnerability assessment in relation to droughts and reduction of damages to houses.

2. Methods

2.1 DK model HIP 100m

The hydrological Information and Prognosis system (HIP) has been developed from 2017-2020 as part of the Danish digitalization strategy on data on topography, climate, and water. As part of HIP, a national hydrological model (DK-model HIP) has been developed and used for historical period simulations as well as climate change impact runs delivered to the portal (in Danish, see https://hip.dataforsyningen.dk/). The model uses data on the entire hydrological cycle to calculate the water cycle in a coupled manner, from precipitation to 2D overland flow, to processes in the root zone to 3D saturated zone flow as well as river runoff. The parameterization of the saturated zone is based on a nationwide hydrogeological interpretation (FOHM). Furthermore, the model incorporates 28 different land uses and 9 different soil types. The DK-model has been under ongoing development since the late 1990's. Recently this model has been used for the EU Water Framework Directive plan gap analysis and river basin management planning, nitrate calculations in groundwater, monitoring of nutrient loads to the sea, mapping groundwater protection as well as several ongoing research projects (Stisen et al. 2019; Henriksen et al. 2021). The structure of MIKE SHE, the hydrological model code used for the DK-model, is shown in Figure 1.

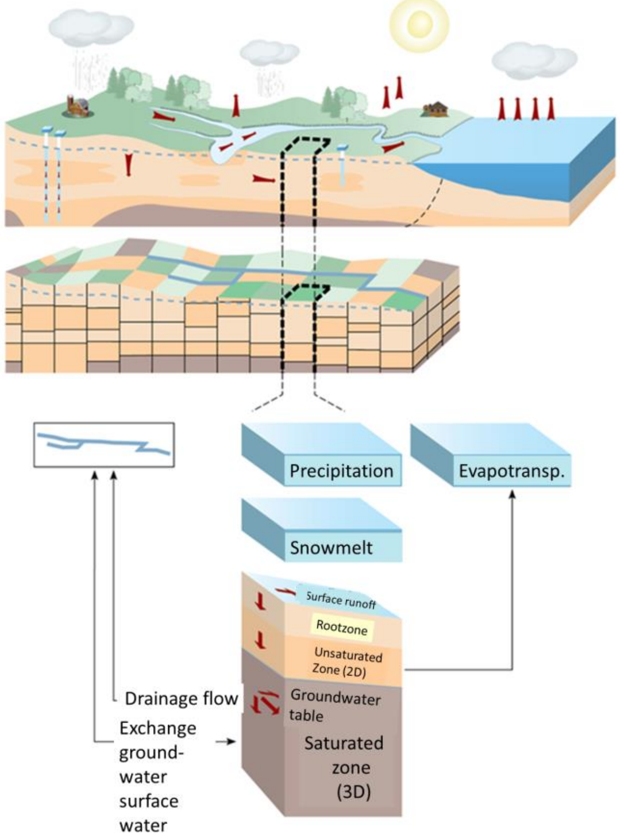


Figure 1. The structure of MIKE SHE which is the model code used in the DK-model HIP.

The DK-model HIP is an integrated, distributed hydrological model with a focus on the simulation of depth to shallow groundwater close to the ground, the water content in the root zone, water flow in watercourses, and boundary conditions for local models. It consists of the following elements: (i) a 500 m model used for calibration, boundary conditions, and climate projections for a total of 22 climate models (DK-model HIP 500 m), (ii) a 100 m model calibrated based on 10 sub-catchment-models and validated at the domain level (DK model HIP 100 m), (iii) a high-resolution machine learning version describing depth to groundwater for winter and summer situation based on a historical period (DK-model HIP10 m ML) (Koch et al. 2021) and (iv) a machine learning downscaling from 500 m to 100 m of climate change-induced changes (Schneider et al. 2022) in depth to terrestrial groundwater for RCP4.5 and RCP8.5 in the near and distant future relative to the reference period. Finally, performance and accuracy of the model are transparent for users, by comparison with available observed datasets. The purpose of the national model is an accuracy level comparable with 'a screening model'.

The DK-model HIP was calibrated and validated with data from approx. 300 river discharge gauging stations, several ten-thousands of wells with groundwater level observations, and more than thousands of selected lakes representative of groundwater level.

Statistical processing of historical period simulations has been performed for:

1. depth to groundwater,
2. water content in the root zone
3. streamflow data.

for the period 1990-2019 (both years incl.). Model simulations of depth to the groundwater table and water content in the root zone are stored and made available in a 100x100 m grid with daily time steps. In addition, data for 3D flow are available for boundary conditions for all calculation layers every 90 days and potential for all calculation layers every 15 days, as well as groundwater recharge to the saturated zone stored every day.

For the *depth to the groundwater*, the delivery consists of time series (day, month, season, year) and descriptive statistics: • Maximum, minimum, average, standard deviation (period, season, and month) • Exceeding (1, 5, 10, 25, 50, 75, 90, 95 and 99) (period, season and month) • T-events (2-, 5-, 10-, 20-, 50- and 100-year events) (entire period only) • The probability of exceeding / the frequency of groundwater close to the ground closer than 1m / 2m below the ground (only the whole period).

For the *water saturation in the root zone*, the delivery consists of time series (day, month, season, year) and descriptive statistics: • Mean, standard deviation, and exceedance percentiles 99 (minimum) and 1 (maximum) (for the entire period, season and month) The water saturation in the root zone is the fraction of the actual water content divided by the maximum water content[m^3/m^3]. The water saturation in the root zone is unitless and is measured between 0 and 1 (as volume fraction). In MIKE SHE, the water saturation is controlled by precipitation, actual evaporation, and variation in the root zone depth. Summer periods are defined as June, July, and August, and winter periods as December, January, and February.

For *streamflow*, the delivery consists of time series (day, month, season, year) and descriptive statistics (for the entire period, season, and month level) for all water flow points in the model (approximately 62,000 points):

- Maximum, minimum, average, standard deviation (entire period, season, and month)
- Exceeding percentiles (1, 5, 10, 25, 50, 75, 90, 95 and 99) (entire period, season and month)
- T-events (2-, 5-, 10-, 20-, 50- and 100-year events) (for the entire period only)
- Median maximum and median minimum (for the entire period only)

This means that in HIP daily simulated data from the DK-model HIP for soil moisture, groundwater level, streamflow runoff and groundwater boundary conditions are available for the historic period 1990 to 2019. For future climate conditions (intermediate and high climate scenario RCP4.5 and RCP8.5 based on an ensemble of 22 climate models), projected changes to the depth to the groundwater table as well as streamflow are provided. A real-time version with daily updates to all simulated values is under development (HIP real-time model), which will be ready in a first operational version by the end of 2022, and in a final version in real-time and with 5-10 days prognosis data by 2025.

2.2 Drought indices

The calculation of indices is based on daily time series for precipitation, soil moisture, and depth to the phreatic groundwater table, and bi-weekly values for the deeper groundwater levels taken from the DK-model.

There exist a wide range of drought indices in literature. We chose a range of established drought indices that (i) cover a range of drought types (agricultural drought, hydrological drought), (ii) have been used in the Danish context before (Chan et al., 2021, Karlsson et al., 2015), and (iii) can be calculated based on the available output from the DK-model HIP. These drought indices are:

Streamflow drought index (SDI)
The SDI has been developed based on the standardized precipitation index (SPI) (McKee et al. 1993), and is a hydrologic drought index. However, due to the typically skewed distribution of stream flow, the SDI is calculated based on log-transformed values of stream flow:

$$SDI = \frac{Y_{i,j} - \overline{Y}_j}{std_{Y,j}}$$

$$Y_{i,j} = ln(Q_{i,j})$$

where $Y_{i,j}$ is the log-transformed stream flow in the i^{th} year and j^{th} week. $\overline{Y}_j$ and $std_{Y,j}$ are the mean stream flow and respective standard deviation for the j^{th} week across the reference period. Typical values (except for extremely high or low flow conditions) range between -2 and +2, where negative values indicate relatively dry conditions, and positive values relatively wet conditions.

Soil Moisture Deficit Index (SMDI)

The SMDI can be considered an agricultural drought index, as insufficient soil moisture in the root zone adversely affects crop growth. It was originally developed by Narasimhan and Srinivasan (2005) and is calculated in two main steps. First, a weekly moisture deficit is computed for each model grid as

$$SD_{i,j} = \left(\frac{SW_{i,j} - MSW_j}{MSW_j - minSW_j}\right) * 100 \quad if\ SW_{i,j} \leq MSW_j$$

$$SD_{i,j} = \left(\frac{SW_{i,j} - MSW_j}{maxSW_j - MSW_j}\right) * 100 \quad if\ SW_{i,j} > MSW_j$$

where $SD_{i,j}$ is the soil moisture deficit [%] for the i^{th} year and j^{th} week, and $SW_{i,j}$ is the available soil water in the (respective part of the) rootzone for year *i* and week *j*. In our case, due to the use of a simplified representation of the unsaturated zone, the soil water values are determined across the entire rootzone. $minSW_j$, $maxSW_j$, and MSW_j are the minimum, maximum, and median soil water values of week *j* across the reference period.
Similarly, as for the SDI, the inherent seasonality of hydrological variables such as stream flow and soil moisture, is eliminated by using weekly climatology values as reference.

To account for the fact that (agricultural) drought severity also is determined by the drought duration, the SMDI then is calculated based on the weekly soil moisture deficits in an accumulated manner:

$$SMDI_{i,j} = \frac{1}{2} SMDI_{j-1} + \frac{SD_j}{50}$$

where $SMDI_{j-1}$ is last week's SMDI, and SD_j the current soil moisture deficit as calculated above.

Within the reference period, SMDI values will range from -4 to +4, where negative values again indicate relatively dry conditions and vice versa.

Standardized groundwater depth index (SGDI)

The SGDI (e.g., used by Bhuiyan et al., 2006) is formulated based on the SPI. In our case, we calculated the SGDI for two different groundwater tables: (i) the standard groundwater deficit for uppermost groundwater table having a more direct interaction with the surface and surface water as well as vegetation and groundwater dependent ecosystems, as well as (ii) the standard groundwater deficit for piezometric head level in deeper aquifers (Quaternary sand 3). It is calculated for each model grid as:

$$SGDI_{i,j} = \frac{D_{i,j} - \overline{D}_j}{std_{D,j}}$$

where $D_{i,j}$ is the depth to the groundwater table in the i^{th} year and j^{th} week. $\overline{D}_j$ and $std_{D,j}$ are the mean depth to the groundwater table and respective standard deviation for the j^{th} week across the reference period. Again, typical values range from -2 (dry) to +2 (wet).

The reference period for all drought indices was 1990 to 2019.

3. Results

3.1 Case 1: Drought-damaged houses – The Natural Hazards Council

3.1.1 Background

The summer of 2018, being the driest in 99 years causing 2018 to be referred to as "Annus horribilies", caused damage to many houses in Denmark, likely due to land subsidence. Such damages could not be covered by insurances. Since July 2022 the Natural Hazards Council (Naturskaderådet, former Stormrådet) is officially responsible for managing a new natural drought damage scheme for damages to buildings. Before July 2022, the Council's focus was limited to storm surge and flooding damages from rivers and lakes.

Data on reported damages to houses was collected from a public Facebook group "Drought-affected homeowners 2018" (locations indicated in Figure 3). Besides that, insurance companies received a total of 182 damage claims.

3.1.2 Plastic clays

Plastic clay, a soil type that has left its mark on the landscape in many places and has been a major challenge for structural engineers, is found in some places in the Danish subsurface. The clay is very deformable, which comes from the clay's ability to contain a lot of water.

Damages on buildings can be due to several factors. Drying out of clay under houses is a frequent cause of damage in Denmark. The geotechnical engineering company GEO has carried out over 700 investigations of fracture-damaged properties in the past (more than 30 years). The data from GEO's archives reveals that almost one third of all fracture-damaged properties are due to the drying out of clay under the house's foundation. Other reasons for damages are due to foundation on fill soil or organic soil (52%), and non-specified reasons (18%).

In a JRC technical report on drought in Europa (Cammalleri et al. 2021) drought vulnerability of buildings and infrastructure is dependent on: "composition soils swell and shrink with moisture changes. If the soil shrinkage is very pronounced under drought conditions, this can cause serious damage to buildings and infrastructure. For instance, in France soil subsidence has caused as much damage as floods in recent years. The effects of drought could be aggravated due to aquifer over-exploitation".

This means that droughts only lead to damage on built environment, if there at the same time is a pronounced soil or clay shrinkage, because of drought conditions. The hypothesis is that the plastic clay in the soil/subsurface has a high sensitivity to events with drying, and that drought damages will be more likely in areas with plastic clay deposits.

Plastic clay is a fat, red, green, or grey clay species that easily can be shaped with the hands. The plastic clay in Denmark originates from the geological time periods Mid-Late Palaeocene and Eocene from 54 to 38 million years ago (Figure 2). As they are deposited before Quaternary, they experienced the glacial cycles that occurred in the Quaternary period. The evolution and movement of the ice masses above the Palaeocene and Eocene clays highly influenced their stress history and the plastic clays is dislocated as rafts or megablocks up into the glacial derived sediments (Heilmann-Clausen et al. 1985). Glaciotectonic deformation has a large impact on the litho-stratigraphical variability of Quaternary deposits and the shallow subsurface Pre-Quaternary sediments (Jakobsen 1996). Glaciotectonic deformation is widespread in Denmark, including dislocation of Pre-Quaternary bedrocks (Figure 4). Plastic clay is known from Røsnæs and the Aarhus region; near and under the Little Belt; and at Fehmarn Belt.

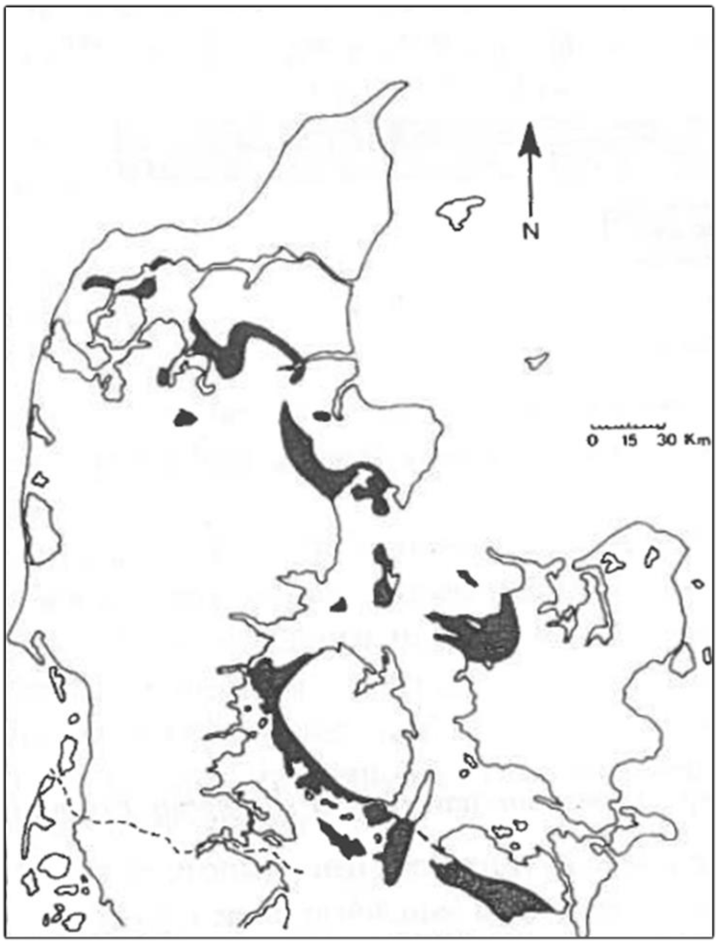


Figure 2. Geological map of the Pre-Quaternary deposits in Denmark. The dark coloured areas show the distribution of the upper Palaeocene and Eocene deposits that contains the plastic clay formations (from Nielsen 1995).

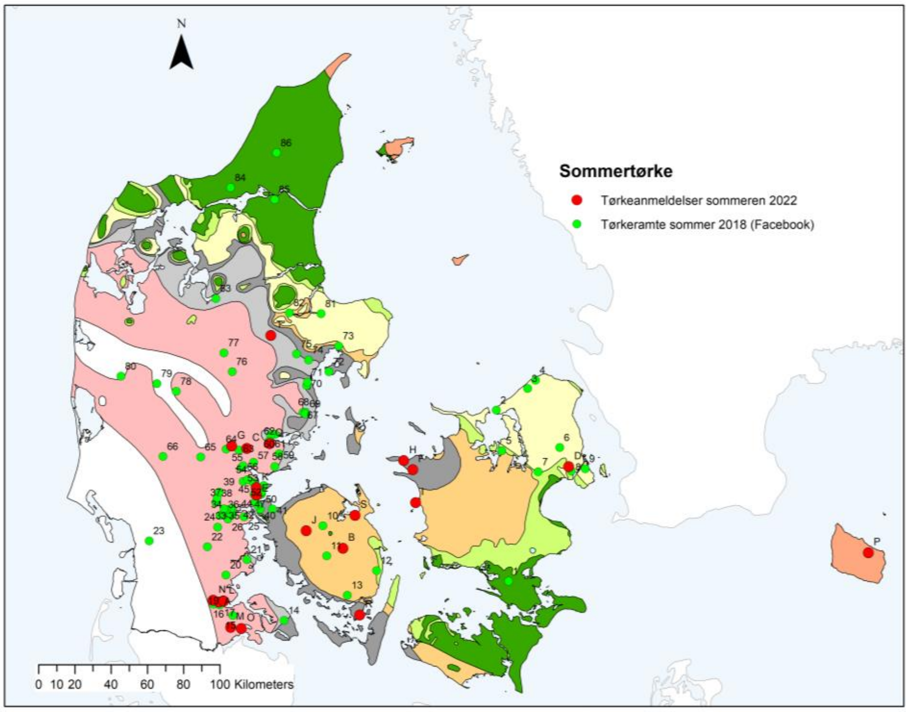


Figure 3. Location of drought-damaged house owners in summer 2018 (green dots) and summer 2022 (as of end of September 2022, red dots) shown on a background map showing Pre-Quaternary deposits.

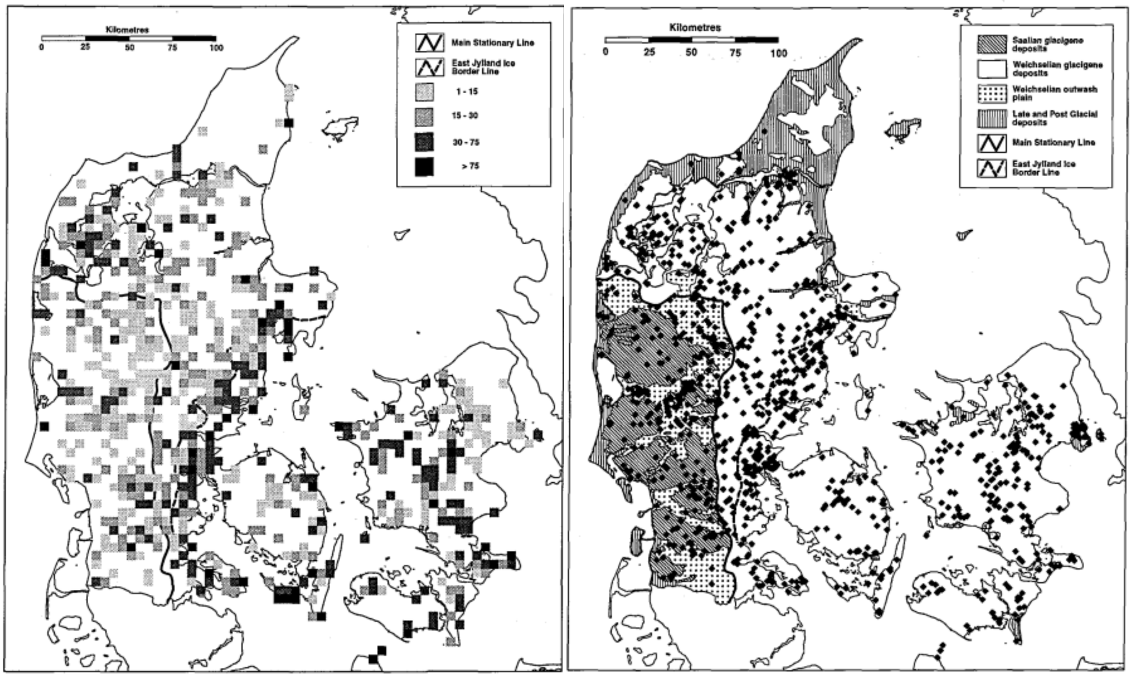


Figure 4. Left: Map of glaciotectonic deformation recorded in wells. Each grid cell is showing the intensity of deformation in each 5x5km grid cell as number of wells with recorded deformation in ‰ of the total number of wells. Right: Distribution of wells with logs in which dislocated Pre-Quaternary bedrock (including plastic clays) is recorded in the glacial derived sediments (from Jakobsen 1996).

The late Palaeocene plastic clays from Holmehus, Æbleø and Kerteminde Marl formations have almost same composition of clay minerals: smectites with swelling properties (70-80%), illite (20-25%), chlorite and kaolinite (0-1%). The same three formations have a grain size distribution of sand (1-10%), silt (30-40%) and clay (50-75%) total weight. It should be noted that there are other clay deposits in Denmark with not quite as high a content of smectite, which presumably can also be a risk for building foundations during periods of extreme drought. It can be clay deposits with smectite content in Branden clay (30-40%), Skive Clay (approx. 50%, Brejning formation (30-40%) and Gram clay in Miocene deposits.

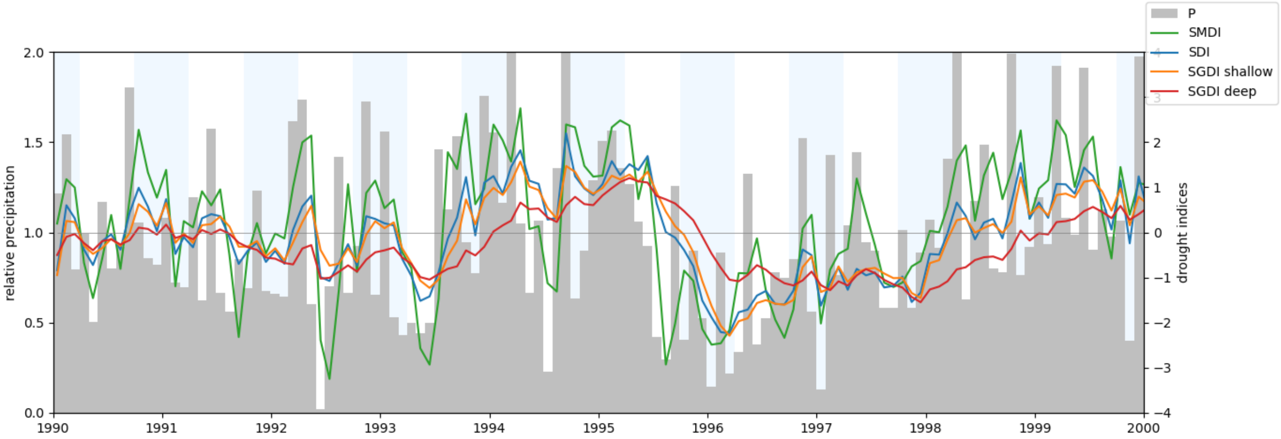
3.1.3 Time series of precipiation and drought indices for streamflow (SDI), soil moisture (SMDI), as well as shallow and deep groundwater (SGDI) for Denmark for 1990 to 2019

Figure 5 shows monthly values of precipitation (P), together with soil moisture deficit index (SMDI), streamflow drought index (SDI) and standardized groundwater depth index for both the shallow (SGDI-s) and deep (SGDI-d; Quartenary sand layer 3) groundwater table, as average across Denmark based on DK model HIP 100 m results.

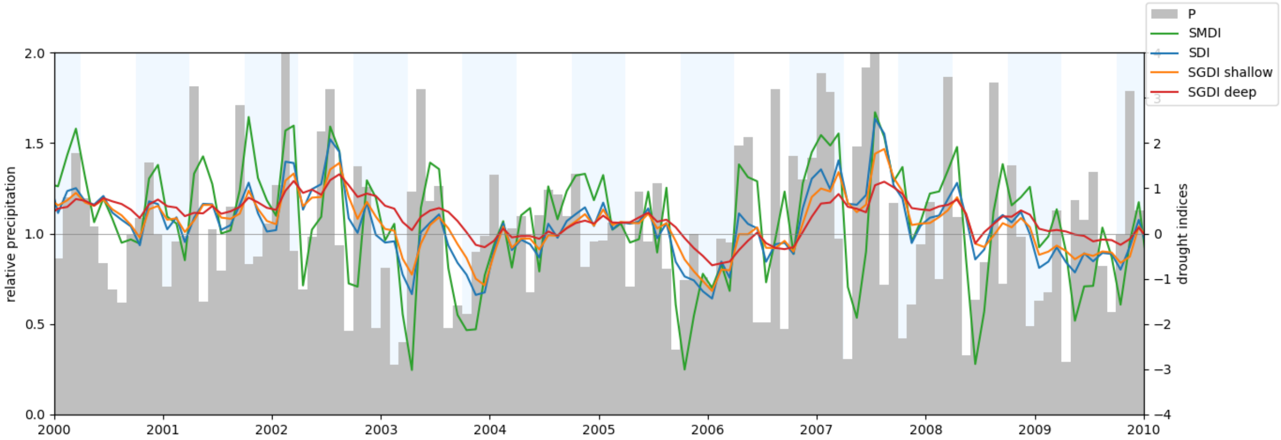
If we look at the dry summer 2018, it is clear from Figure 5 that the three months June, July and August were very dry in terms of precipitation (monthly P at ~0.25 to 0.40 of its average values). SDI was relatively high/wet in April 2018, but low/dry for June-July. Shallow and deep groundwater depth indices (SGDI-s and SGDI-d) were not low/dry before the autumn, and the following year.

Figure 6 shows the same indices, however only for the summers (week 1 to 34) of 2018 and 2022 on a weekly basis. When the HIP real-time model will become available in real-time in the coming years (project period 2022-2025), updated timeseries with monthly or weekly drought indices and anomalies, as shown in Figure 5 and 6, can in principle be shown for any region or subarea, and that can better illustrate the different drought indices for different regions in Denmark. The HIP data model and statistical data are shown with monthly, seasonal and yearly statistics, which would fit well with how data is displayed in Figure 5.

1990-1999



2000-2009



2010-2019

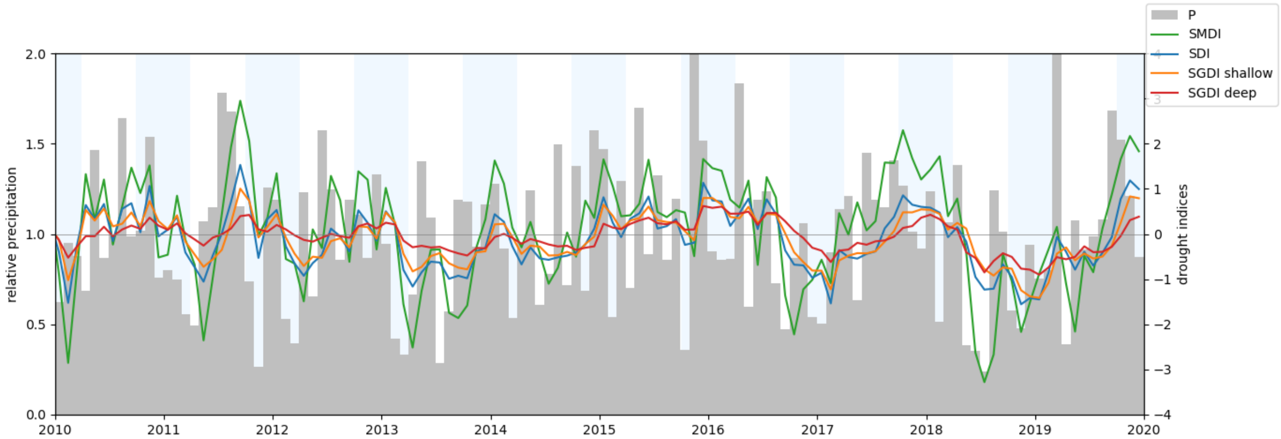
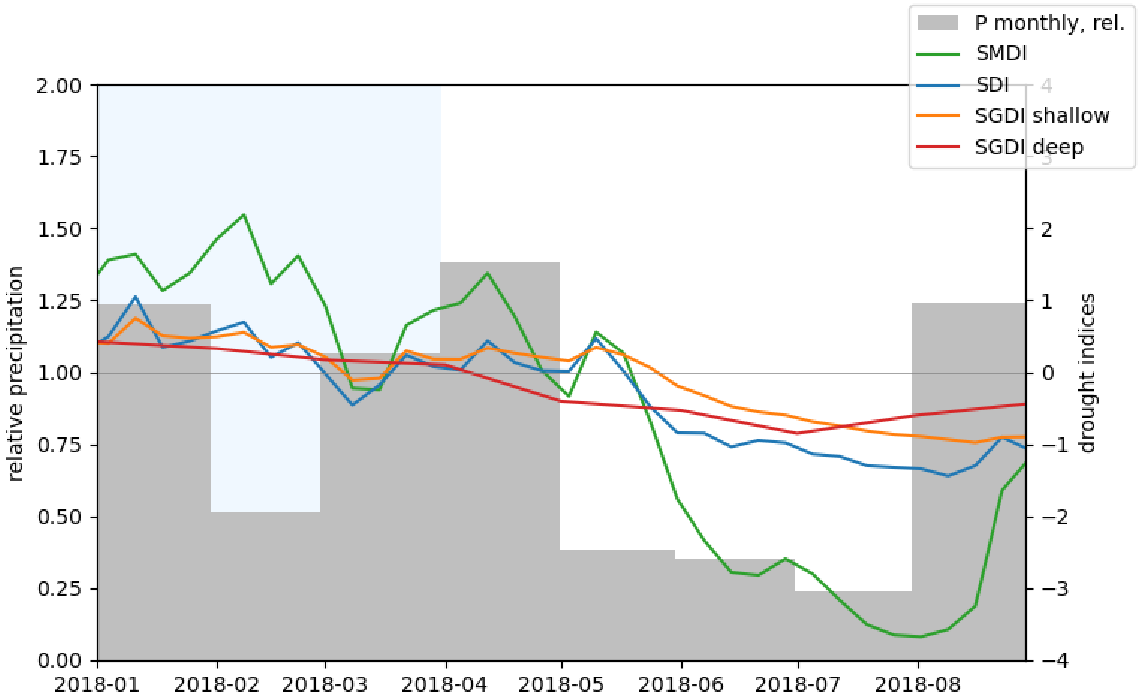


Figure 5. Monthly values for precipitation (P, grey bars, relative to average monthly precipitation; left y-axis), soil moisture deficit index (SMDI – green, right y-axis), streamflow drought index (SDI - blue) and standardized groundwater depth index (SGDI shallow: orange and SGDI deep: red). Average values across Denmark. The winter months (October to March each year) are shaded in the background.



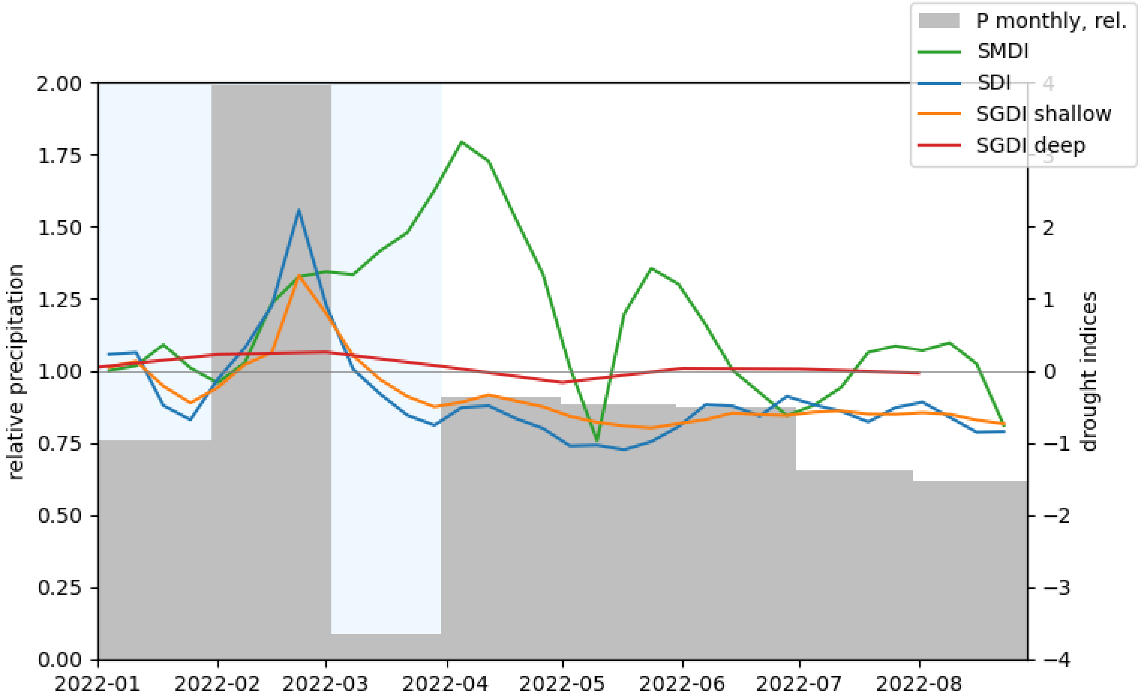


Figure 6. Weekly values of SDI, SMDI, SGDI shallow and SGDI deep for January – august 2018 (upper) and 2022 (lower). Average indices for Denmark.

The difference between 2018 and 2022 is clear when we compare the two graphs in Figure 6. In 2018, February was relatively dry in terms of precipitation, and also May to July only had precipitation in the range of 0.25 to 0.40 of the usually monthly values. However, due to high groundwater levels (having a longer memory), the low precipitation in February had no significant impact on drought indices for soil moisture and discharge.

The consistently low precipitation in the summer months, on the other hand, impacted soil moisture drought significantly, and – with a delay – also the drought indices for shallow and deep groundwater, which dropped from neutral values around 0 in late April to extreme drought of almost -4 in the beginning of August 2018. In 2022, February was extremely wet in terms of precipitation, leading to clear responses in streamflow and shallow groundwater. The following extremely dry March brought SDI and SMDI back to normal and slightly dry levels. This was followed by only moderately dry spring and summer months (with precipitation in the range from ~0.70 to 0.90 of average values). This only lead to moderate streamflow and shallow groundwater droughts in 2022, and soil moisture was close to normal values.

When looking at SMDI, two phenomena specific to the used model setup (DK-model HIP) must be mentioned: Due to the setup of the hydrological model, soil moisture values can only be extracted aggregated across the entire rootzone, which spans up to ~2 m dependent on season, soil and vegetation type. Furthermore, this means that in periods of a growing rootzone (typically in spring when vegetation is developing), the root zone expands and can reach into the saturated zone, i.e. into the groundwater.

This explains the increase of the soil moisture visible in March 2022, despite the lack of precipitation: In this period, the root zone is expanding into deeper layers, where it in parts reaches the groundwater table (which is standing high after a wet February). By this, soil moisture, as average across the root zone, increases.
Still, the summer of 2022 clearly is a less severe drought in Denmark than the summer of 2018. This is illustrated in Figure 7 which shows the same average monthly drought indices as in Figure 5, but as a rasterized plot, but here we extended until July 2022 as an option for how anomalies could be shown from HIP realtime model on a monthly basis.

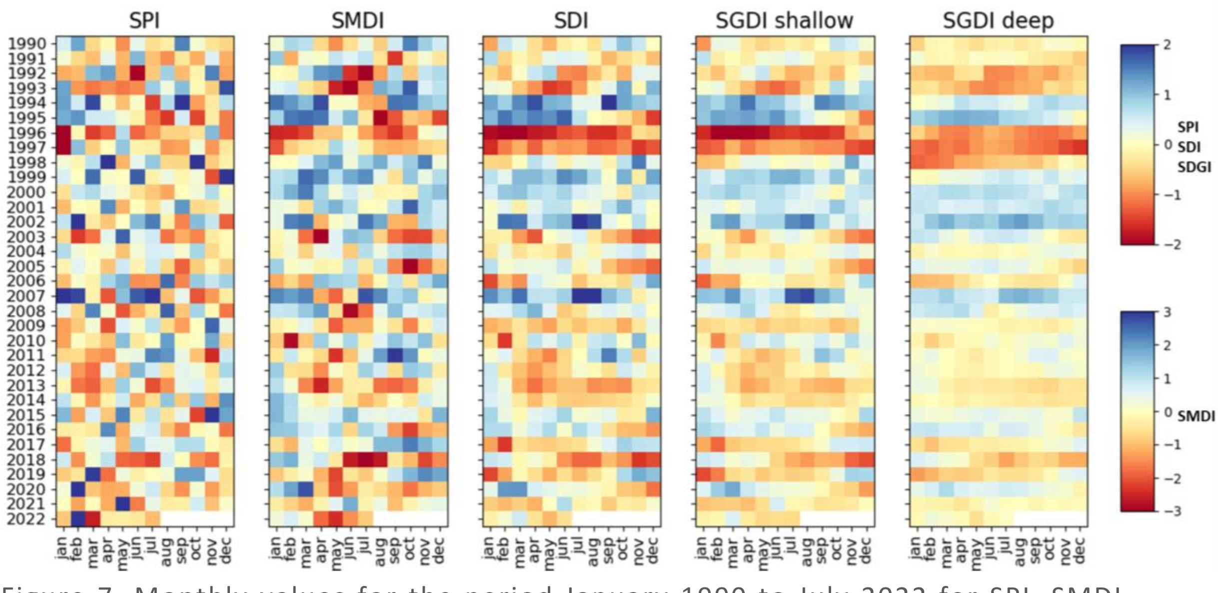


Figure 7. Monthly values for the period January 1990 to July 2022 for SPI, SMDI, SDI, SGDI shallow and SGDI deep, as average across Denmark.

In the next section we will compare the summer season (JJA) for 2018 and 2022 and include the drought damage datasets available (Facebook group for 2018 and drought damages reports received by Naturskaderådet for drought damages in 2022).

3.1.4 Results of drought indices for soil moisture (SMDI) and groundwater level (SGDI) for selected summer seasons 2018 and 2022 with spatial variations for Denmark

Figure 8 compares the 2018 summer season (JJA) average values for SMDI, SDI, and SGDI shallow and deep. Figure 9 shows the same comparison, only for the 2022 summer season. Drought index values are classified into classes as typically reported in literature (e.g. Chan et al., 2021):

- Mild drought: index between 0 to -1
- Moderate drought: index between -1 to -1.5 for SDI and SGDI; -1 to -2 for SMDI
- Severe drought: index between -1.5 to -2 for SDI and SGDI; -2 to -3 for SMDI
- Extreme drought: index below -2 for SDI and SGDI; below -3 for SMDI

The approximate locations of Facebook group drought damages for 2018 and drought damages for 2022 (received by Naturskaderådet) are indicated in Figure 8 and Figure 9. As those maps show summer season averages (JJA), there are limitations in the analysis. For example, drought duration also has an impact on some effects of drought, which cannot directly be deducted from the summer season averages. Still, the comparison of SMDI for 2018 and 2022 shows that: (i) the summer of 2018 had extremely dry soils (practically all of Denmark is suffering from extreme or severe drought conditions), (ii) whereas in summer 2022 the majority of Denmark only suffered from moderate soil moisture drought. Despite the extremely dry soils in summer 2018, the groundwater was not in the same extreme drought condition, and also shows more regional variations. This is mostly due to the slower response of groundwater storage to precipitation anomalies, and the relatively wet preceding winter of 2017/18. 2022 was in general less severely dry, with the exception of the most south-eastern parts of Denmark.

With respect to the large variations in the SGDI-d, including also areas with high groundwater levels in the deeper layers, it has to be noted that part of this variation can be due to varying groundwater extraction amounts, which are part of the model and, hence, affect deeper groundwater levels. In other words: The wetter conditions in the deeper groundwater levels (high positive SDGI-d values) that can be seen e.g. on Fyn can be partly related to lower groundwater extractions in the years 2018 and 2022 compared to the average of the reference period 1990 to 2019.

When looking at the locations of the reported drought damages in summer 2018, some correlation between SMDI and SGDI-s can be seen: More drought damages seem to have been reported from areas with particularly severe drought indices. This impression can be confirmed by a simple statistical analysis, where the average drought index is more negative (i.e. drier) for the drought damage locations than for the entire country. For 2022, there seems to be a similar correlation, at least for SGDI-s. However, the dataset for 2022 is not complete yet. In general, more information and a more detailed investigation are needed to conclude on correlations between drought damages due to land subsidence and different drought indices, including not only the severity, but also duration and timing.

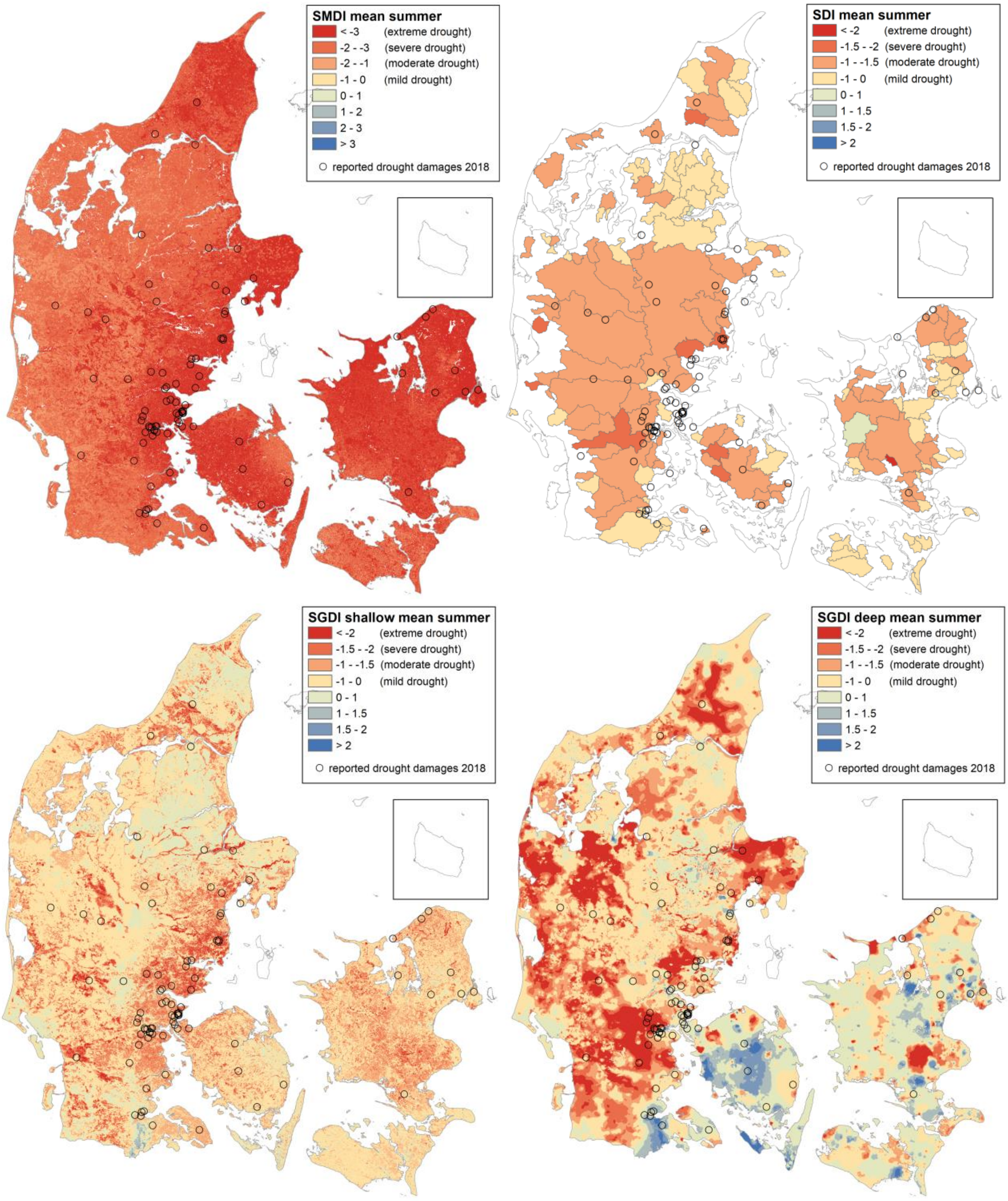


Figure 8. Comparison of seasonal results for summer 2018 of soil moisture deficit index (SMDI), streamflow drought index (SDI) and shallow and deep groundwater depth indices (SGDI-s and SGDI-d), together with (approximate) locations of reported drought damages in 2018 (shown with 'o' based on Facebook group data).

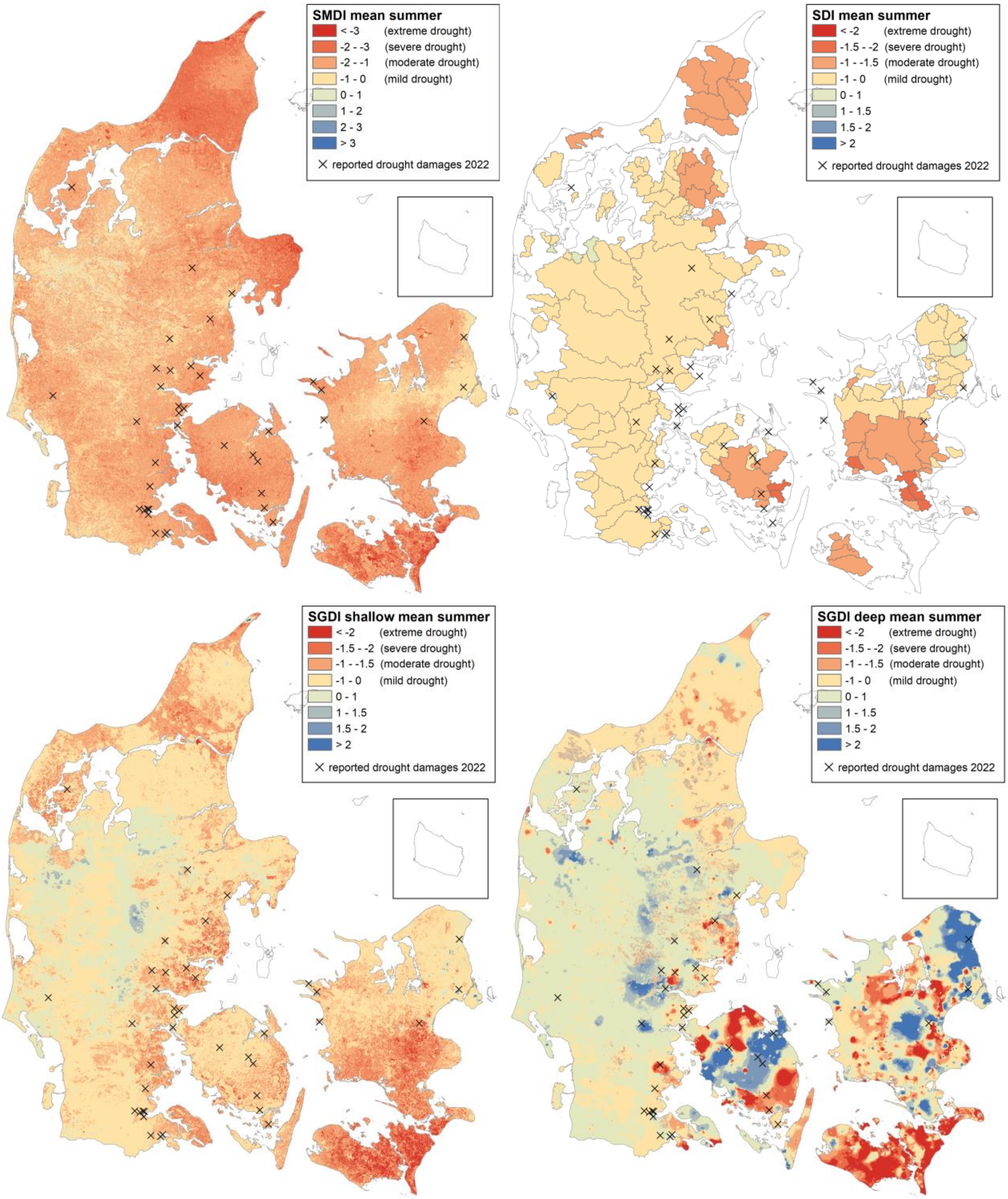


Figure 9. Comparison of seasonal results for summer 2022 of soil moisture deficit index (SMDI), streamflow drought index (SDI) and shallow and deep groundwater depth indices (SGDI-s and SGDI-d), together with (approximate) locations of reported drought damages (shown with ‘x’; reported to Naturskaderådet between July 1 until end of September 2022).

3.1.5 Summary of results of testing drought indices

Based on the results presented in Figure 5 to Figure 9 the following can be summarized:

- Summer 2018 was characterized by a moderate groundwater drought, especially in areas with shallow groundwater tables (south-eastern Jylland, Sjælland, Fyn). In other areas e.g. in the central and western part of Jylland the SGDI mean summer was less negative. The moderate groundwater drought in 2018 is due to the dry summer, and not more severe due to the wet preceding winter.
- Summer 2022 was not at the same degree dry as 2018. Many parts of Denmark had rather wet soil moisture (eastern part of Jutland etc.) in 2022. SGDI however, in some parts of Denmark were more dry than 2018, and in other parts less dry than 2018.
- More severe groundwater droughts (e.g. 1996) are caused by dry winters rather than dry summers (see Appendix and 1996)
- The soil moisture deficit (SMDI) shows severe drought conditions for 2018 all across Denmark.
- When compared with other drought years like 1996, soil moisture in 1996 was only moderately reduced during the summer period. For winter dry years like 1996, or years where a larger part of the drought occurs either before or after the summer period (in autumn), SGDI and SMDI applied for the summer period may result in a less robust assessment of drought situations. Therefore, monthly values of SGDI and SMDI throughout the evolving drought period might give a stronger signal, compared to the results achieved for 1996.
- SMDI shows that the soil water content was extremely low for 2018, at the same time as we experienced a more moderate SDI (streamflow runoff drought), whereas shallow groundwater did not experience equally dry conditions (SGDI shallow). The deep groundwater in some areas was relatively dry (many areas in Jutland, Northern Fyn and Northern Sjælland). Other areas were more wet.
- A multifaceted drought index of all the indices SMDI, SDI, SGDI shallow and deep seems to be the most appropriate for a general drought evaluation. For analysis of drought damages, e.g., at Facebook group damages sites, it could be important to know the exact date of the damage and the day the incident was sent to the insurance company. Without this knowledge it is difficult to fully assess the vulnerability of clay soils and clay layers in the saturated zone, and how to weight the different indices. For the summer period, only SMDI is fully developed for the 2018 summer drought, the other indicators SDI, SGDI shallow and deep require more time to fully evolve (SDI has less memory than SGDI shallow, but SGDI deep can take years before it reaches the minimum level for a certain summer and/or summer-winter-summer drought.
- In Denmark the years 2019 and 2020 were less dry than observed in western Europe. Large increases in multi-year droughts in north-western Europe in a warmer climate are foreseen (Wiel et al. 2022).

3.2 Case 2: Agricultural drought

3.2.1 Background

The 2018 drought was expected to trigger high losses in the Danish agricultural. In August 2018 it was evaluated that the losses could reach almost 6.4 billion Danish crowns ($1.03 billion), according to agriculture institution SEGES Innovation (DR, 2018). The fear was, that Denmark's harvest of wheat, barley, and rye could fall by about 40% from previous years. On top of this, the drought had hit fodder production and forced farmers to buy more expensive fodder from third parties.

However, according to a report from the Department of Food and Resource Economics (IFRO) in early 2019 (Schou 2019), the drought turned out to have had less of an impact on Danish agriculture than first expected. The report found that the agriculture industry endured direct losses of 4.1 billion crowns due to the unseasonably dry weather – 2.3 billion crowns less than what was expected by the Danish Agriculture and Food Council in August 2018.

The weather in the second half of 2017 was relatively wet. The weather in 2018 started relatively normal. January was relatively mild, whereas February and especially March 2018 were characterized by colder temperatures. Thus, the establishment of spring seeds started a little later than usual. In early May, the weather suddenly turned into summer. It was as if the weather went straight from winter to summer – as in a real continental climate – with lots of sunshine and warmth and no rain. By the end of May 2018, Denmark had already had 17 meteorological summer days (days where the temperature exceeds 25 °C) against 13 summer days for the whole of 2017. May 2018 thus became the warmest May on record since measurements started in 1874. The summer continued in both June and July with one record after another. Overall, there were 993 solar hours in May, June, and July, compared to 719 on average for 2006-15. The year 2018 was in every way a record year with seven heat records and four sunshine records.

Rainfall – as shown in Figure 10 – was relatively low in May, June, and July. May and June in particular are essential for the grain crops, as the plants in these months have the greatest overgrowth and thus water consumption. In mid-May, the drought began to show itself visually in many fields, and already at the end of May, it was critical in many places.

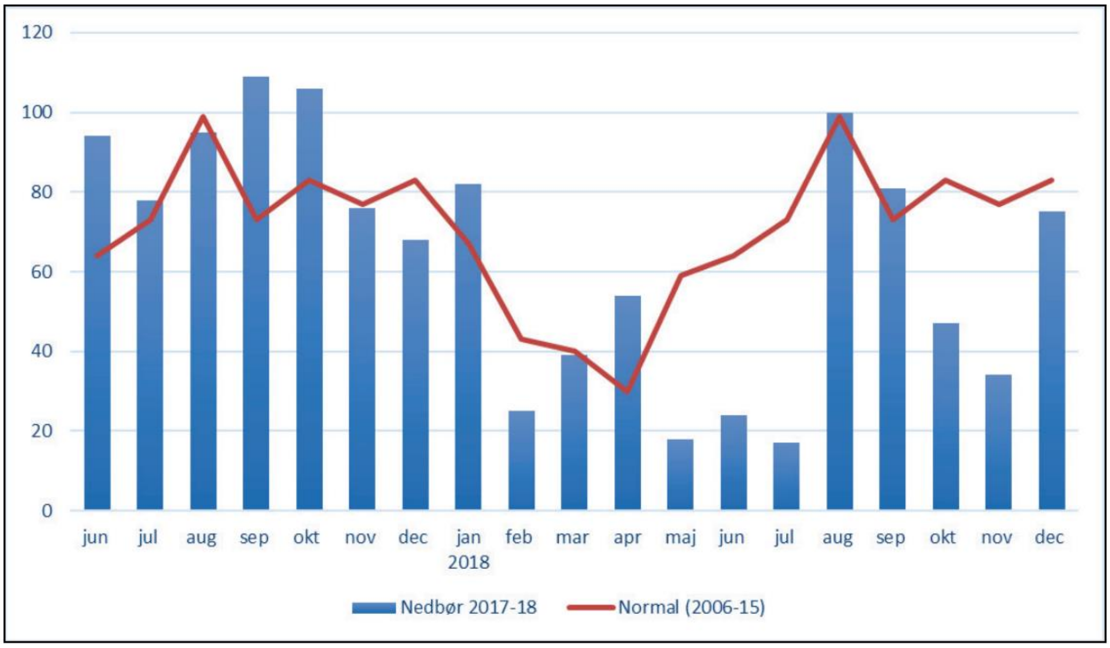


Figure 10. Precipitation in mm for 2017-18 Source: Sølver (2019).

However, the average rainfall figures mask a large variation. Bornholm was thus affected by drought already from mid-April, while the rest of the country got about 30 mm rain in late April. Also at the end of May, there were several very local thunder storms with up to 50mm of rain favouring lucky farmers at a critical time. Although the drought later became nationwide, these local showers often have a big effect on yield.

As seen from Figure 10 it was mainly the very dry conditions from May to July, and again dry conditions in autumn (October-November) which caused the impacts on SMDI, SDI, SGDI shallow and deep (compare Figure 5, Figure 6). The period before May 2018 did not have distinct anomalies.

In addition to precipitation, the root zone capacity of the soil (ability to retain water) also has a decisive importance in a dry year. The root zone capacity depends on the crop (the length of the roots), as well as the clay and humus content in the soil. Thus, the root zone capacity of spring barley on sandy soils is only 50-80 mm, while on clay soils it is often 150-200 mm (Madsen et al., 1992).

Areas with clayey soils (typically east Jutland and the islands) therefore generally have much better tolerance to drought compared to (non irrigated) sandy soil. Thus, the drought of 2018 had different consequences depending on the type of soil but was nevertheless so elongated that the crops on all types of soil were affected. The drought did not end until the last days of July when most of the country got thunder shower events. By this time, much of the harvesting work was over in record time, and most of the crops and straw, therefore, came dry and easy in-house.

Although August was also slightly warmer than usual, both rainfall and sunshine were normalized. Also, September became normal, and slowly the soil's water content was normalized. The consequences for some of the late crops, e.g. sugar beet and roughage, thus became mitigated to a certain degree.

The severity of a summer drought not only depends on summer precipitation. Also, initial conditions (how wet or dry the soil is at the beginning of summer and the growing season) are important. The most vulnerable period of growth is during flowering. The 2018 drought had rather severe consequences for crops, due to rather wet conditions in Autumn 2017 and early Spring 2018. This limited the development of root depth and after the shift from wet to very dry conditions, left the growing crops vulnerable to the very dry conditions during spring. The recent year 2022 also experienced a dry period in spring, but here conditions were more normal in autumn 2021 and early spring 2022. This means that root zone development has provided a more robust growth situation during the evolving period with dry conditions.

According to Søren Kolind (senior advisor, SEGES), there is no comprehensive dataset describing which agricultural areas have had drought damages. The best indicator according to Søren Kolind might be the water deficit required for optimal irrigation. Søren Kolind suggests looking into the work by DCA (Ten Damme and Neuman Andersen 2018), focusing on gross irrigation water requirements.

Figure 11 show the modelled irrigation demand for irrigated land in DK-model domain 5 (Central Jutland, IrrNoLimit). The dry summer 2018 had an irrigation demand around 170 mm/year from January to July 2018 (the simulation was only carried out until 31/8 2018). As seen in the figure, this makes 2018 the year with the highest irrigation demand in the historical period since 1990. The second highest demand is seen for 1992 (140 mm/year), and the third highest for 2008 (120 mm/year). This comply well with the SMDI results in Figure 7.

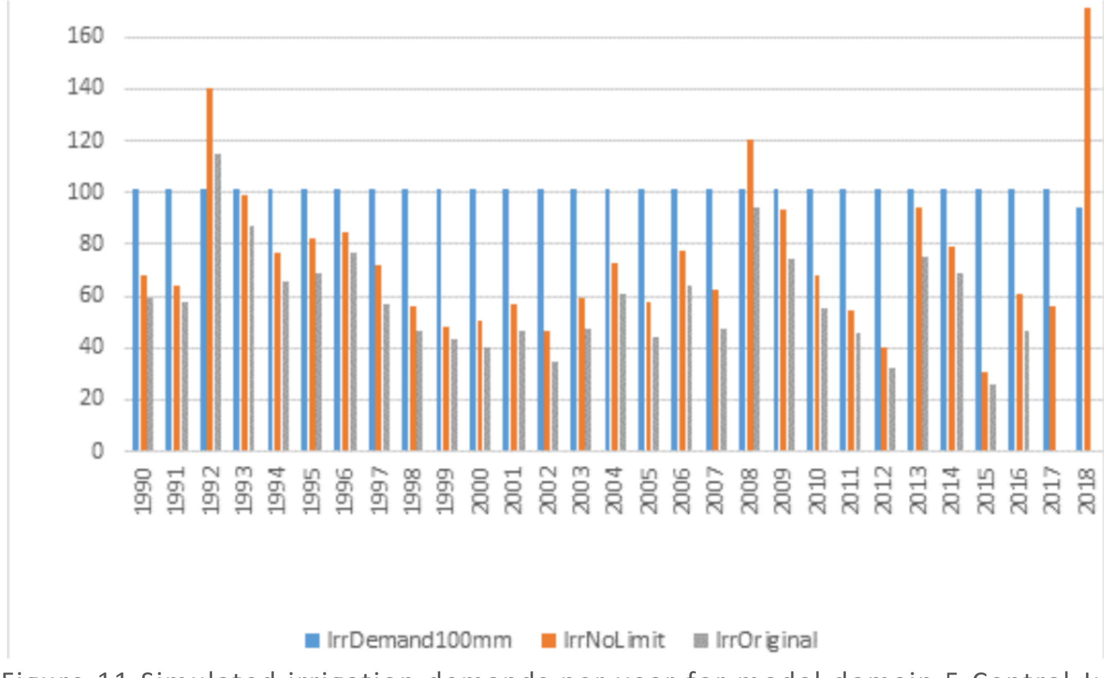


Figure 11 Simulated irrigation demands per year for model domain 5 Central Jutland for the period January 1990 - July 2018 by use of DK model 2019 (REF Vandweb user manual). Grey: Original DK model 2019 setup (Stisen et al. 2019), Blue: fixed irrigation of 100mm per year, and Orange: Irrigation demand without any yearly max limit (of 100 mm/year). The grey bars are missing for 2017 and 2018 because the original DK model 2019 was only run until the end of 2016.

Figure 12 also illustrates the simulation with DK-model 2019 (Grey) (but only until 2016) with a slightly different setup compared to the irrigation no-limit setup. Therefore, the water demand-based simulation as used in the DK model and the original irrigation demand simulation are ‘scenario’ setups, which consider different assumptions about how regulation impacts the actual irrigation of irrigated areas.

The DK-model HIP (and its previous version, the DK-model 2019) automatically irrigates specified areas based on irrigation demand estimated based on soil moisture deficit and crop demand. Drought indicators solely based on soil moisture time series, mean and standard deviations, as in many used indices, therefore provide a ‘relative indicator’, and not an ‘absolute measure’ of the actual soil moisture demand. What farmers do will also depend on costs for irrigation pumps, and cost-benefit evaluations of what are the most valuable use of the resources (e.g. instead of irrigating crops, farmers eventually would focus on the crops used in dairy production, etc.). Another issue is that the impacts of a drought may be most severe when the drought evolves during the flowering period, whereas a drought during harvest (like in 2018) may not provide an equal amount of damage costs.

The vulnerability to drought, therefore, is dependent on how soil moisture develops and is compensated by irrigation, during the flowering period for the different crops on different soil types, but the socioeconomic consequences of agricultural drought is also very much related to the market when selling the products where a year with extended drought elsewhere, like 2022 result in increased prices for crops. In the DK-model (HIP or other versions) growth seasons (Leaf area index, LAI, and root depth development) for the incorporated vegetations are ‘fixed’, and will not automatically adapt to, e.g., an earlier onset of the vegetation period due to an uncommonly warm spring.

Another way forward could be to make it more transparent which areas are irrigated, and increase the awareness of the users about the ‘relative nature’ of drought indices especially for irrigated grids or vulnerable sandy soils. Soil type and vegetation in the data that are made available in real-time would communicate how to use the screening data provided by the HIP real-time and 5-10 days prognosis model.

3.2.2 Historical and ecological perspective on the 2018 agricultural drought

The drought of 2018 over central and Northern Europa was notable for its severity, exceptionally warm and exceptionally dry May to July. Spring rapidly transitioned into an extreme summer drought (Peters et al. 2020), and with an epicenter over UK and Scandinavia, where crops and forest rarely experience such an extreme event with high summer temperatures and soil moisture deficits (see also Figure 1012). Learning about resilience and drought impacts from this rare event in terms of resilience and broader aspects for ecosystem services is, therefore, worth describing here in brief based on the paper by Peters et al. (2020).

For the public, the long period without rainfall, causing crops and grassland to wilt early in a massive ‘brown down’ of the landscape might have been an “eye-opener” for climate change concerns. A brown down which was later confirmed by analysis of MODIS-based leaf area index (LAI) and normalized difference vegetation index (NDVI), showing a record surface of Europe falling in the lowest quantile of the greenness of the past two decades (Peters et al. 2020). This type of agricultural (summer) drought was created by meteorological drought: excessive heat and drought over western Europe, the western USA, and the Caspian Sea were driven by an atmospheric drought (phase-locked) which is expected to become more frequent in the future warmer climate (Kornhuber et al. 2019/2020; McCarthy et al. 2019; Kendon et al. 2019; Peters et al. 2020). Compared with the previous agricultural droughts in Europe since 2000, the summer of 2018 registered the largest extent of 24-38 Mha across Europe, compared to previous events in 2003 (20-28 Mha) and 2010 (10-14 Mha), and the 2018 event was centred around Germany, Poland, most of Scandinavia and the Baltic countries (with larger extent of boreal forest and high latitude ecosystems and in previous events). Compared to other years, 2018 experienced a sharp transition between average-to-wet conditions in late winter to strong soil-water deficits in summer. In Figure 1212, results for previous droughts over Europa 2003, 2010, and 2018 are shown (Peters et al., 2020).

For Denmark, during the Central/northern European droughts in 2003, 2010 and 2018, the dry conditions illustrated with the indices were also very much affected by the extreme drought in the late spring (see Figure 6 and 7). The temperature map, however, shows that Denmark was within the 5% high-end temperatures (neither 2003 nor 2010 had such an extreme heatwave as in 2018 Denmark). Net radiation was extremely high for the 2018 event for Denmark. Finally, soil moisture was extremely low in the 2018 event for all of Denmark, which is in agreement with the results based on SMDI calculated with the DK model HIP in Figure 8 (for 2018). It is clear that Denmark was severely affected by the 2018 European drought event in terms of both summer period temperature, net radiation, and soil moisture for the entire country, but for summer rain in the northern a bit less affected part.
Peters et al. (2020) describe how rare the 2018 event has been: “Model simulations reproduce conditions similar to the 2018 European drought for only 4 years out of 875 years in historical runs and projections (Toreti et al., 2019)”; however, a summer drought as intense as 2018 could become a common occurrence in Central Europa as early as 2043 due to climate change. Another study shows an increase of up to 26% in the areas affected by summer drought (Samaniego et al., 2018).

From the papers on the special issue described in Peters et al. (2020) the following research themes can be summarized related to soil moisture and agricultural drought:

- Soil moisture stress has a clear role of on vegetation but a better understanding is needed and better forecast skills of soil moisture (along different depths) are required as a main ecological controlling variable.
- Ecological impacts present an accumulation of effects over longer time scales, with consecutive winter and spring conditions priming the soil and vegetation for larger summer impacts. Answers to questions like what is needed in coupled land-surface modelling to capture such impacts in seasonal forecasts of weather, vegetation state, and carbon exchange, are of high value for society.

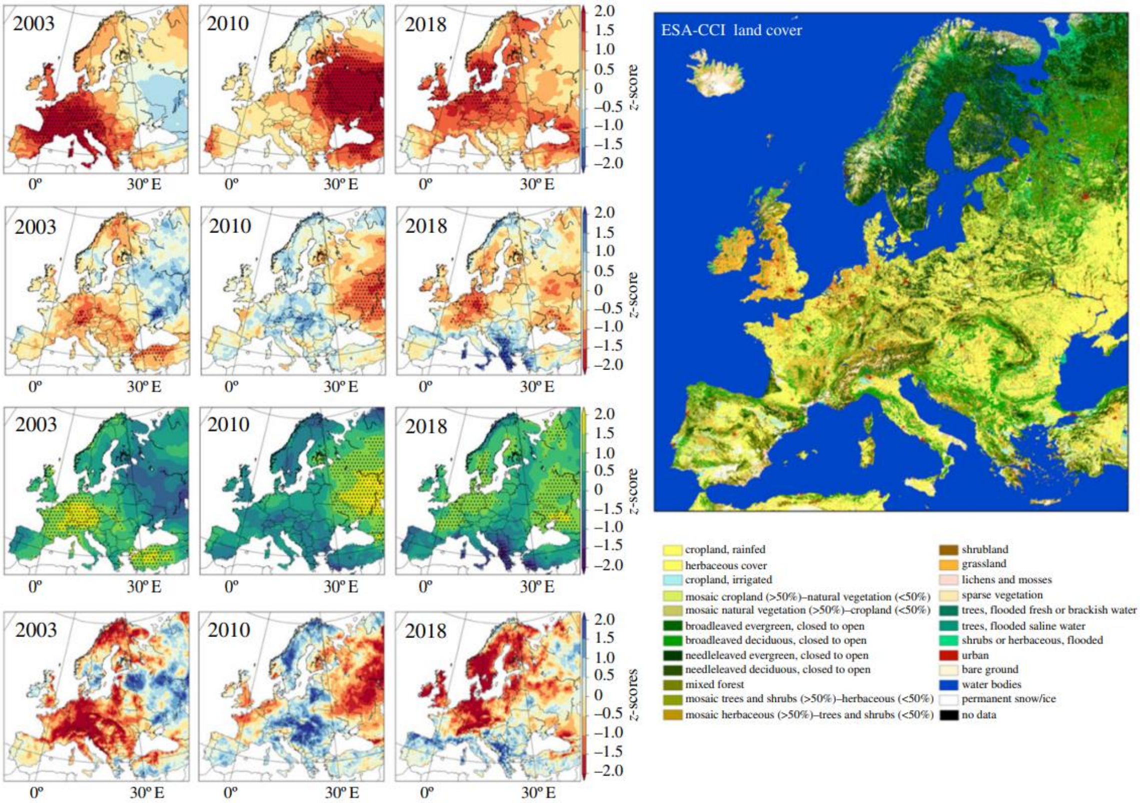


Figure 12. Three recent extreme summers (2003, 2010, and 2018) placed in a 40-year perspective of temperature (top row), summer rainfall (second row), incoming radiation (third row), and soil moisture (bottom row) anomaly. Z-scores refers to the standardized anomalies for the reference period 1979-2018. The stippling indicates pixels where registered anomalies were in the top 5% (temperature and radiation) or lowest 5% (rainfall). The European land-cover map from ESA-CCI Land Cover for the year 2018 is shown in the right panel (Source: Peters et al., 2020). The three consecutive dry summers in western Europe 2018-2020 (van der Wiel et al., 2022) have revealed a need for a better understanding of such multi-year drought and winter and summer.

- Different networks of observation play synergetic roles. Satellite remote sensing is emerging as an exciting way to see (proxies of) the top levels of the soils dry out, such as the brown down of vegetation, loss of optimal canopy structure, crop development rates, and fires. However, process understanding is needed which requires long-term monitoring. This includes all scales and all coupled systems affected by drought: soils, roots, trunks, leaves, canopies, fields, turbulent surface layers, planetary boundary layers, ecosystems, weather systems, and continents. Research should focus on integrating these data streams, across the different disciplines.

3.3 Reflection on aggregation in our analysis of droughts

- The indices tested here is applied as a (weekly) soil water deficit, calculated based on (modelled) current and min and max values for relative soil moisture. Using a weekly climatology; i.e. it is relative to a reference period! It takes into account the past values; in the accumulated way of calculating it gives an indication of drought severity on weakly basis (Figure 6), and here shown aggregated to monthly (Figure 5 and 7) and seasonal values (Figure 8 and 9)
- It looks like a feasible approach to show time series with monthly percentiles of soil moisture (SM), depth to phreatic (DTP), deep groundwater piezometric head, and precipitation (P) (see also below and example from Tidjeman et al. 2022 in Figure 1313)
- The HIP portal is able to show absolute values of depth to shallow groundwater and streamflow (under development) as daily values. Statistical data is shown for monthly and seasonal values and with percentiles and return values of high flow on annual basis. Aggregation to monthly indices can therefore be handled with the present HIP datamodel and seems as an feasible approach when showing long timeseries as done in Figure 7. The question is if this aggregation is sufficient also for the users for the HIP portal, this has to be further clarified. In the Figures 8 and 9 the indices is shown on a seasonal basis for the whole of Denmark. Here the questions is if such maps should be shown on a monthly and weekly basis. Furthermore, Figure 7 could be shown for subareas e.g. on domain level (7 domains in DK-model), resource areas (58 subareas), ID15 scale (approximately 3000 subcatchments). This also need further discussion with the users of HIP portal.

To summarize: SMDI, SDI and SGDI shallow and deep seem to be very useful aggregated to a monthly value for illustrating longer term variation in time. However, these indices can also be calculated for weekly values, and updated daily in a real-time environment (in the upcoming HIP real-time model), including prognosis for the next 5 to 10 days. This would allow for fast detection of developing drought situations.

In situations of extreme drought, the European Drought Monitoring system (EDO) has forecast 3-month prognosis of drought risks by use of an ensemble of models. Longer term seasonal forecasts could be relevant to consider, since drought evolves over longer terms.

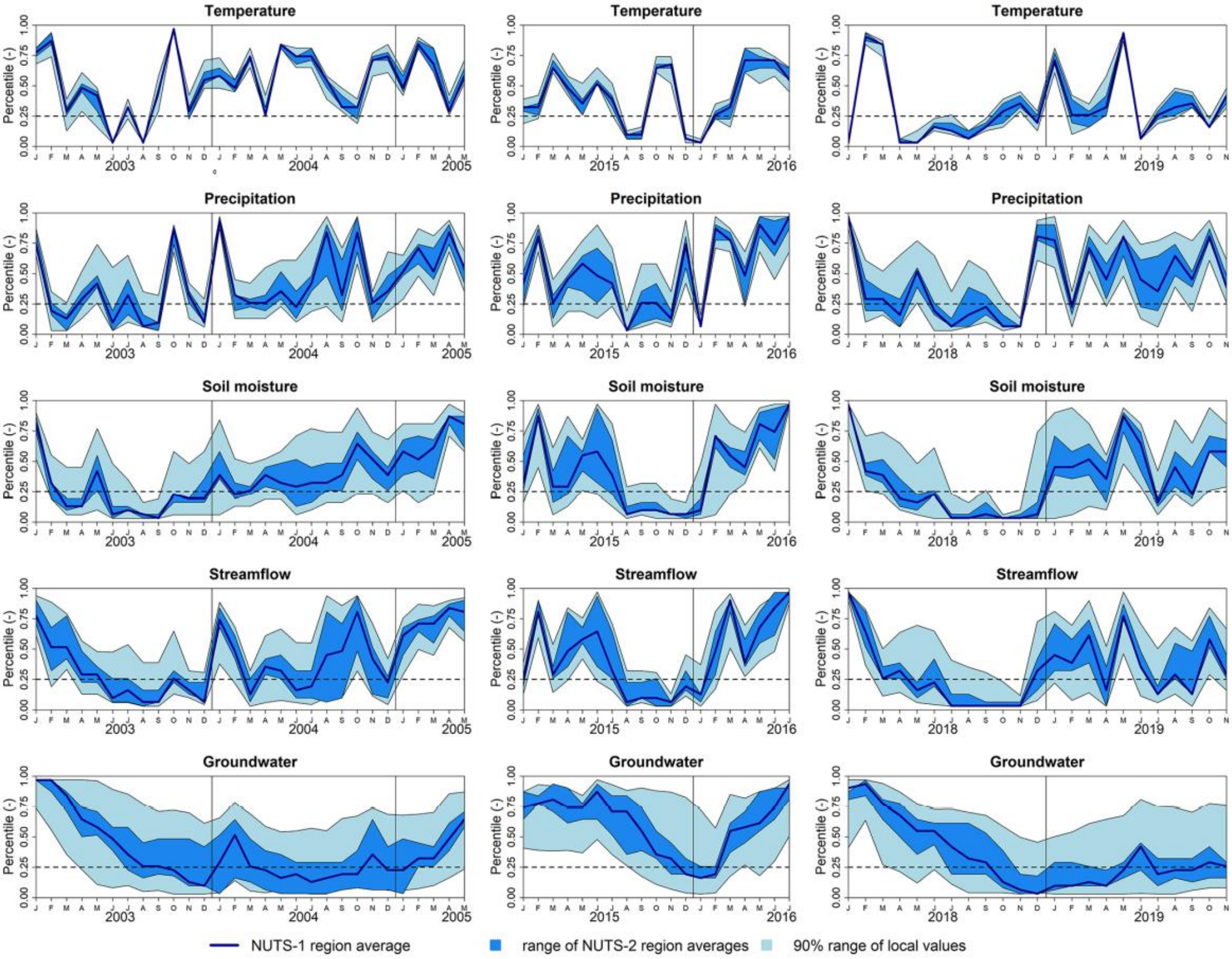


Figure 13. Illustration of aggregated time series of temperature, precipitation, soil moisture, streamflow, and groundwater (Tidjeman et al., 2022) for multiyear events.

4. Discussion

4.1 Drought periods in the 1990-2019 historical HIP period

We calculated the monthly values for several drought indices for 1990-2019 for all of Denmark (Figure 5) and identified that the driest month (in terms of precipitation) occurred in June 1992. This caused the second lowest SMDI monthly value in the subsequent month, July 1992. The lowest SMDI month in the entire period occurred in July 2018 after three consecutive months with low precipitation starting in May 2018. Based on soil moisture, 1995 was drier than 1996, but the duration of the SMDI drought in 1996 was longer. Periods with high soil moisture were 1998, 1999-2002, 2004-2005, 2007, 2010, 2012, 2015-2016, 2017 and 2019.

Looking at streamflow drought index (SDI) the summer of 1996 was the most extreme followed by 2018. 1993 was also a dry SDI summer. The wet summers was 2007, 1994-1995, 1998-2002, 2004-2005, 2010 and 2015-2016.

SGDI for shallow groundwater was lowest in early 1996 followed by late 2018. For deep groundwater, SGDI had lowest values in late 1997 followed by summer 1992-1993. Also, early 2006, 2018 and 2019 had relatively low values of this index. The wettest winters can be observed for spring 1995, followed by autumn 2007, 2015-2017 and 2020.

Soil moisture drought is mainly sensitive to dry summers like 2018 with three dry consecutive months or very extreme low rainfall like 1992 with one very dry month. At the other end SGDI deep groundwater is mainly driven by winter anomalies with high precipitation as seen for 1993-1994 and 2006-2007.

4.2 Propagation of drought indices

The propagation of drought indices follows a cascading impact process, moving from immediate fast responses, to slower dynamics. All starts with meteorological drought (precipitation), which is followed by relatively quick responses in the soil moisture index (SMDI). On the dry end, this can be seen in the most extreme fashion for 2018, but is also clear for 1992 and 1995 (see Figure 5 and Figure 7). Next comes streamflow (SDI), which has more inertia than responses in soil moisture, but still faster dynamics than the shallow groundwater. Deeper groundwater has the most long-term memory up to several years (e.g. 1993 to 1995, 1995 to 1998, 2013 to 2016). This general behaviour of the modelled drought indices can be seen very well in Figure 7, and follows the physical understanding of the hydrologic cycle.
Besides the different dynamics, some other phenomena can be seen the two figures:
The most decisive for groundwater drought (or excess, i.e. positive values for the drought index) is winter precipitation. This is explained by the fact that, in Denmark, the majority of groundwater recharge happens during winter months. Hence, groundwater droughts happen mostly after dry winters (such as 1995/96), and groundwater reservoirs can be refilled again after wet winters (such as 2006/07).

Dry summers, on the other hand, have mostly an immediate impact on SMDI (and SDI). One of the reasons why 2018 maybe had no larger effect on Denmark is the fact that the winter 2017/18 had been relatively normal, leaving groundwater levels at normal to slightly above average levels in the beginning of the summer 2018, which offered some buffer – at least for groundwater.

4.3 Discussion of results and aggregation level

Figure 5 and Figure 6 show monthly timeseries for the drought indices, aggregated to the entire country. Figure 8 and Figure 9 show the respective mapped outputs (100 m resolution), aggregated across the three summer months. Aggregation to monthly periods will make the monitoring of evolvement of drought even more informative, and both monthly and seasonal aggregation should be implemented in HIP. Figure 5 is aggregated for all of Denmark; if possible on the HIP portal, it will be shown for subareas like the river basins shown in Figure 5, or on a domain level (for the seven model domains). Also, as all indices are calculated based on the model output resolution (100 m), timeseries can be provided for every single grid.

An aggregation to municipalities or other relevant regions (delineated based on e.g. geology or land use) must be discussed and identified with stakeholders.

4.4 Societal resilience and vulnerability assessment

A posting of damage registrations for buildings (from Facebook group) has been illustrated in Figure 8. However, for the data from 2018 both the exact location of the damage and the exact date is unknown. We can see that the 2018 event was only very extreme for SMDI, and that the period with relatively dry conditions lasted for three months. Whether this affects vulnerability to drought damages of built environment due to land subsidence, we do not know. But the soil moisture for 2018 was very low or extremely low for most of the country (Figure 8 upper left). Compared with SGDI shallow and deep many of the registrations of damages compares with relative dry conditions, but here maps for each month October-November-December 2018 is required in order to identify if locations with damage costs compare well with the driest SGDI shallow or deep index.

An alternative index based on number of days with soil moisture and shallow groundwater levels each year below the 1% percentile across the 30-year reference period (Q01 for soil moisture and shallow groundwater level) for 2018 revealed similarly that Q01 for soil moisture was extremely dry for 2018 across large parts of the country. The same statistics for the shallow groundwater level showed more moderate results. Here more investigation is needed also including SGDI deep, and eventually a more accurate set of coordinates for the damage sites (we only had information about the road not the house number). In case damage vulnerable areas for given hazards of the indices should be better identified, and downscaling of SGDI shallow might be necessary, to investigate further.

The distribution of crops in the description of vegetation in the DK-model is based on a fixed statistical distribution of crop types (i.e. the spatial distribution and seasonality of leaf area index and root depth). For screening purposes this is sufficient, since the soil type is site specific (for each 100x100m grid). However, heterogeneities in soil can be significant at smaller scales, and cause damage costs. Also trees can have roots located near houses which during extreme dry events eventually can cause further drying out of the soil not fully represented by the model setup.

To address these issues, we currently are in the process of updating the DK-model with remote-sensing based parameterization of vegetation parameters, which should address some of the issues above, giving a more realistic image of vegetation distribution controlling evapotranspiration (and, consequently, having impact on soil moisture and groundwater rechage).

The irrigated area is located as a circle around the abstraction well. This can be a wrong assumption especially with very dry years like 2018. If farmers consider some vegetation to have had damages in spring and early summer, they probably will not irrigate these crops, and the model results for such irrigated grids may therefore be erroneous. In other cases, farmer without irrigation permissions, eventually also could have irrigated some lands eventually with a special permission, and the model would also be wrong in such cases.

Use of satellite data could eventually be a relevant thing to consider and investigate. GEUS already has experience with dynamic vegetation and use of data from remote sensing / Earth observation. This could also be further investigated, but would have implications for the design of the HIP real-time project.

5. Conclusion

The year 2018 was the driest year in 99 years which caused an agricultural drought with extremely low soil moisture in most of Denmark. The present report analyses drought indices for soil moisture, streamflow and groundwater for Denmark by use of the DK-model HIP 100 m. The original model results were delivered to the HIP portal with daily values for the historic period 1990 to 2019. All the data, together with climate change impact projections, observation data of streamflow and groundwater levels, etc, are publicly available on hipdata.dk.

Based on aggregated results for the entire Denmark, 2018 was the most extreme year for soil moisture for the summer period (JJA). Other years like 1992 and 1995-96 were also very dry in terms of soil moisture. In addition, the winter 1995-96 was dry, which impacts other hydrological indices like SDI (streamflow) and SGDI shallow groundwater which were more severely dry for these years, compared to 2018.

Comparison of damage registrations based on a Facebook group network comply well with SMDI for summer 2018, with a very few exemptions. The hydrological model (DK model HIP 100 m) delivers good and relevant information about the various indicators for meteorological, agricultural, hydrological and groundwater drought, which should be further analysed as part of the ongoing development of HIP : The historic model runs, together with the upcoming HIP real-time model can serve in early warning and monitoring of the various damages related to various drought types, and consecutive years with dry summers and/or winters.

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Word list

GEUS	Geological Survey of Denmark and Greenland
HIP	Hydrological Information and Prognosis System
RCP8.5	RCP 8.5 refers to the concentration of carbon that delivers global warming at an average of 8.5 watts per square meter across the planet.
PDSI	Palmer Drought Severity Index
SWSI	Surface Water Supply Index
SPI	Standardized Precipitation Index
CMI	Crop Moisture Index
WMO	World Meteorological Organization
GWP	Global Water Partnership
DRI	Drought Reconnaissance Index
SMDI	Soil Moisture Deficit Index
SGDI	Standardized Groundwater Depth Index
SDI	Streamflow Drought Index
JJA	June-July-August
Q01	1 percent quantile
DTP	Depth to Phreatic (depth to uppermost groundwater table)