Delft University of Technology

Master Thesis

Hydraulic eng.

Thesis proposal

Quantifying the risk of consecutive dry and wet periods (cascading hazards) and their impact on flood protection system in the Netherlands

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1 Research description

1.1 Motivation

Floods and droughts affected over three billion people worldwide in the past two decades (United Nations, 2015; WHO, 2021). These so called 'hydro-hazards' are two opposite extremes of the same hydrological cycle (Ward et al., 2020). Traditionally, risk analysts focus on either one of these hydro-hazards to quantify its risk. However, hydro-climatic variables are often interrelated, which means that focusing on a single random variable can be a oversimplification from reality which could lead to incomprehensive risk analysis (Hao et al., 2018). For example, temperature rise and prolonged dry period can undermine the reliability of flood protection systems, exacerbating the risk of flooding when followed by heavy precipitation. AghaKouchak (2018) emphasises the need for risk assessments to look at the interdependencies between these variables (i.e. the multiple events). To achieve a better understanding of these compound hydro-hazards, Visser-Quinn et al. (2019) introduced a systematic methodological framework to identify the hydro-hazard hotspots for the United Kingdom. Following on from this, a transdisciplinary approach to bridge science (modelling consecutive hazards) and practice (engineering approaches) is fundamental for a robust flood management system ensuring spatial quality and safety of local communities.

1.2 Problem definition

The summer of 2020 in the Netherlands was the sixth warmest summer since 1901 and was followed by heavy thunderstorms (KNMI, 2021). These kind of extreme events (e.g. extreme precipitation, extreme and/or prolonged dry periods) are expected to become more frequent and severe, as the climate is changing (IPCC, 2012; Horton et al., 2016; Zscheischler and Seneviratne, 2017; Marx et al., 2018; Hao et al., 2018; Visser-Quinn et al., 2019). The Netherlands its flood management practices are able to withstand extreme events (e.g. high discharges or low discharges), however these standards are based on univariate processes (Stichting Toegepast Onderzoek Waterbeheer, 2019). By adhering the concept of cascading hazards to flood management practices in the light of climate change, this can lead to different risk administration for multiple events such as during the summer of 2020 in the Netherlands.

1.3 Research questions

The foregoing issues raise the following main research question that is going to be answered in this thesis:

> *"What are the hotspots prone to cascading hazards and its implications for flood management practices in the light of a changing climate for the Netherlands?"*

As part of a exploratory research, a case study will be performed on the Wilnis dike slide of 2003. Sub question to be answered for this part are:
PART I - Case study Wilnis

> *SQ 1.1: "What were the drivers for the Wilnis dike slide?"*

> *SQ 1.2: "Is there interdependence between variables (e.g. discharge Lobith, precipitation, temperature)? "*

> *SQ 1.3: "What are other areas that face the same risk in the Netherlands?"*

To answer the main research question the following sub questions are going to be answered:

PART II - Main research

SQ 2.1: "What are the frequencies of dry (e.g., lack of rainfall, low flow) and wet (e.g., heavy precipitation, storm surges) across the Netherlands?"

SQ 2.2: "What is the risk of consecutive dry and wet periods (i.e. cascading hazards) by modelling their interdependence?"

SQ 2.3: "What are the hotspots prone to cascading hazards in the Netherlands?"

SQ 2.4: "What are the consequences of cascading hazards for flood management practices in light of a changing climate?"

1.4 Methodology

As part of the studies to cascading hazards, we will look at the failure of the dike at Wilnis in 2003. The analysis of this disaster event will be performed from a bottom-up approach. By starting with the delineation of this event and subsequently identifying the relevant underlying processes, variables and threshold phenomena, the system performance degrades can be identified (Zscheischler et al., 2019).

After this initial case study, the main research will follow with implications for whole of the Netherlands. First, a quantitative analyses will be performed on the wet (e.g., heavy precipitation, storm surges) and dry (e.g., lack of rainfall, low discharge) including its interdependencies. This will require the application of extreme value analysis (EVA) and methods to quantify interdependence e.g. copulas. Next, the risk will be evaluated, by looking for which locations in the Netherlands are prone to cascading hazards. Last, the implications of climate change on cascading hazards will be analysed, as extreme events (e.g. floods, droughts) are expected to become more frequent and severe as of a changing climate (IPCC, 2012; Horton et al., 2016; Zscheischler and Seneviratne, 2017; Hao et al., 2018; Visser-Quinn et al., 2019).

The last sub questions has broad application possibilities. The extent of answers will be dependent on the rate of advance in this thesis. This question will be first answered qualitatively, i.e. "What kind of flood management practices are affected by the considered risk?". If possible one or more of these practices will be further investigated in particular.

2 Literature study

In this chapter various concepts related to the research topic are explained. Both as a general concept and if applicable with respect to the Netherlands. The strategy for performing this literature study and its related activities are described in Appendix A.

2.1 Drought

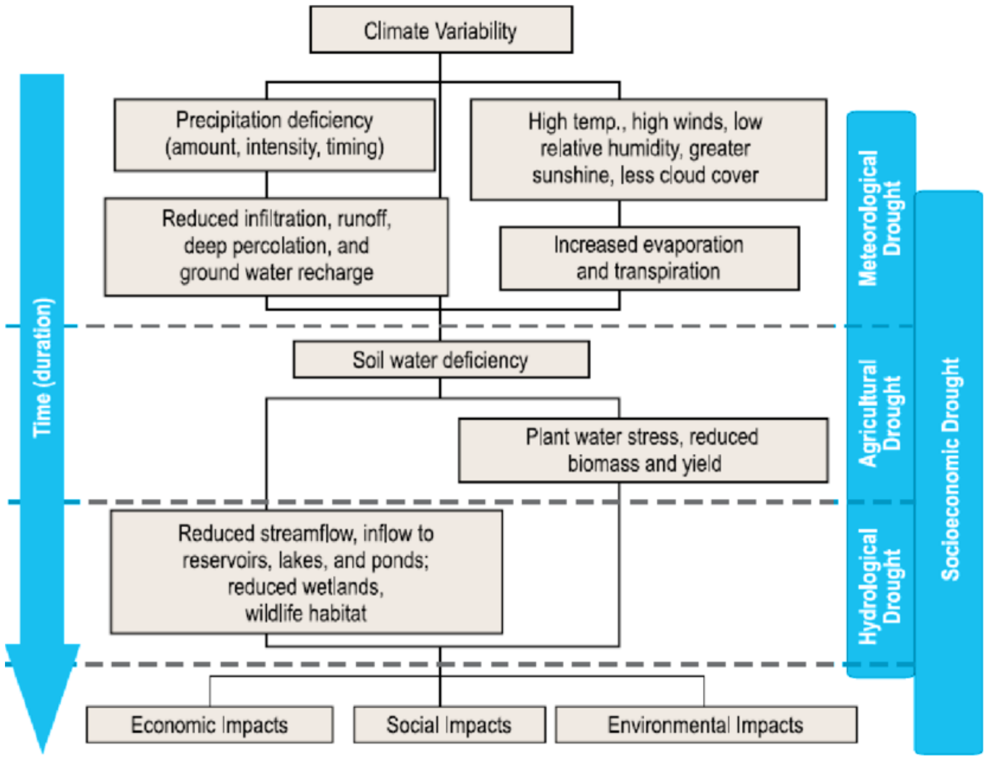
2.1.1 Introduction on drought

Drought is a natural hazard, just like floods, earthquakes or cyclones. However, drought is a "creeping phenomenon" and does not show a as predictable and distinct onset and ending as the other hazards. Simply said, drought can be considered as a shortage of water and is often relative to a long term average condition or climate. This definition is relative simplistic, whereas other definitions for drought are dependent on the application it is used for.

Drought events affect nature and people all over the world. It can be observed multiple ways. Most people in the Netherlands notice the effects of drought in the shape of desiccation damage to nature or their gardens. For the agricultural sector it can lead to crop damages. Additionally, drought can lead to low water levels in rivers and canals, which can lead to limitations in transport by vessels and has effect on aquatic ecosystems. These examples are only a hand full of what meaning drought can have. Drought is a complex and multifaceted concept for the various fields of research drought is used, such as meteorology, ecology and hydrology. It is therefore essential to choose the point of view on drought for the selected application, as there can not be a comprehensive definition of drought (Wilhite and Glantz, 1985).

2.1.2 Choosing a point of view on drought

The various implications drought can have can be confusing. In turn, this can lead to indecision and inaction. Having no clear understanding of the concept can lead to ad hoc response to problems faced from drought. In the literature, four types of drought definitions based on the control hydro-meteorological variable (i.e., drought driver) investigated, e.g., meteorological drought, agricultural drought, hydrological drought, socio-economic drought (Wilhite and Glantz, 1985; Mishra and Singh, 2010), soil moisture drought and ecological drought (van Loon, 2015). These definitions may overlap, e.g. socio-economic drought can occur during the various stages of meteorological drought, agricultural drought and hydrological drought (Figure 1). As of this reason, the definitions of drought available in literature are distinguished based on their drivers or impacts. An additional version based on figure 1 can be found in Appendix B.



Source: National Drought Mitigation Center, University of Nebraska-Lincoln, USA

Figure 1: Schematization of common drought definitions found in literature. Presented by their name, processes and their underlying relations. Dependent on the duration (vertical) drought will move to a next phase or definition. Starting with meteorological drought having anomalies in weather e.g. lack of precipitation or increased temperature. As a result, a deficiency in soil water can arise (phase two: Agricultural drought). Finally, this can result in a deficiency for open water or ground water, meaning hydrological drought. From National Drought Mitigation Center

2.1.3 Drought definitions based on drivers

The drought definitions based on drivers are meteorological drought, soil moisture drought and hydrological drought. These definitions are explained in more detail in the following sections. Common indicators and indices found in literature per type of drought are also presented.

Meteorological drought

Meteorological drought is defined based on a deficiency in precipitation for a certain area and over a certain period of time. This type of drought is most prevalent definition. Furthermore it is site specific, whereas the quantification of drought (e.g.the duration and deficiencies) is relative to and in relation with the local climate (Wilhite and Glantz, 1985). Meteorological drought indicators should be independent of physical properties of the site it is measured (Wanders et al., 2010). A vast number of indices to quantify and monitor meteorological drought are available. These are (almost) always based on precipitation data. Some definitions involve other parameters such as humidity, temperature, wind or vapor pressure. However, these definitions of drought are not commonly used. Common indicators are (Keyantash, 2002; Hayes, 2009; Wanders et al., 2010; van Loon, 2013; Svoboda and Fuchs, 2017; Weijers, 2020):

- **Standardized Precipitation Index (SPI)** by McKee et al. (1993) is designed to quantify the precipitation deficit for multiple time scales. It requires monthly data, where no specific length of the time series is required. It can be calculated with as little as 20 years of data, but its robustness increases with longer time frames. On the time series a probability distribution is fitted. This indicator can be less suitable for dry climates, as fitting distributions to the data can be problematic (Wanders et al., 2010). Furthermore, often absolute volumes of water deficits relative to a normal are required, which is not possible with this indicator as it only works in relative terms (van Loon, 2013).

- **Rainfall deciles** is a relative easy to calculate index, which is also the reason why the Australian Drought Watch System uses this indicator (van Loon, 2013). Average values obtained from long-term observations are compared with monthly aggregated precipitation data (Gibbs and Maher, 1967). This long-term observation is one of the drawbacks of this indicator. Furthermore, according to Keyantash (2002) this indicator does not suit highly seasonal and extremely dry regions, whereas the 90% required for this method is surpassed by a sequence of zeros.

- The **Standardized Precipitation Evapotranspiration Index (SPEI)** is an alternative for the SPI where it also includes potential evapotranspiration (Vicente-Serrano et al., 2010). It works similar as the SPI, as it also requires to fit a distribution to the time series data.

- Byun and Wilhite (1999) introduced the **Effective Drought Index (EDI)** which only requires daily precipitation data to calculate the effective precipitation (EP) and several of its statistical values (i.e. mean, deviation and the latter its standardized value). As of the sole parameter required and its frequency, it is widely applicable and useful to determine onsets and ends of drought events (Svoboda and Fuchs, 2017).

Soil moisture drought

Soil moisture drought refers to deficits in moisture of the upper soil layer (primarily in the root zone). This type of drought is often referred to as agricultural drought, though has a broader meaning as soil moisture drought is associated with crop loss or yield loss, e.g. ecosystems and infrastructure (van Loon, 2015). To monitor or to identify soil moisture drought conditions common indicators and indices are (Keyantash, 2002; Hayes, 2009; Wanders et al., 2010; van Loon, 2013; Svoboda and Fuchs, 2017; Weijers, 2020):

- **Palmer Drought Severity Index (PDSI)**, introduced by Palmer (1965), is widely around the world. The method is often considered as a hydrological accounting system as it works as a water balance model for soil moisture. It requires serially complete data of monthly temperature and precipitation.

- **Crop Moisture Index (CMI)** is a modified version of PDSI (see indices for meteorological drought), Palmer (1968), suitable to monitor short-term responses of the soil moisture and is meteorological driven. It uses observed or simulated data of precipitation, and temperature to determine the potential evapotranspiration. Additionally it uses its preceding CMI value to determine its subsequent value.

- **Soil moisture Deficit Index (SMDI)** is developed by Narasimhan and Srinivasan (2005) and can be used to detect short-term drought conditions. It requires specific soil moisture information from approximately 0.6 to 1.8 meters soil depth. It is well applicable for identifying soil moisture drought for the agricultural sector.

- **Soil Moisture Index (SMI)** (Hunt et al., 2008) is derived by calculating the difference between the local vegetation wilting point and the field capacity. This index ranges from -5 to 5, where -5 is extreme drought, 0 is no drought and a value of 5 could mean a potential of flash flooding. The index is space and time specific.

Hydrological drought

Hydrological drought is the results of a reduction in water levels of rivers, surface water and ground water. It is often caused by sustaining meteorological and agricultural drought. Water Authorities mostly refer to this type of drought. Common indicators for this type of drought are (Keyantash, 2002; Hayes, 2009; Wanders et al., 2010; van Loon, 2013; Svoboda and Fuchs, 2017; Weijers, 2020):

- **River discharge** Van Loon et al. (2010). Where the discharge is used relative to a customary appointed threshold.
- **Hydrological Drought Index (HDI)**, widely used (Zhao et al., 2019), and is a function of the Standardized Streamflow Index (SSI) (Shukla and Wood, 2008).
- **Surface Water Supply Index (SWSI)** by Shafer and Dezman (1982). It uses historical records of precipitation, accumulated snow, water storage and streamflow for the calculation of exceedance probabilities.

2.1.4 Drought definitions based on impact

Three drought definitions based on impact are described below. Socio-economic drought can be considered as the umbrella term for all drought definitions based on impact, whereas agricultural drought and ecological drought are mere examples of this type of drought.

Socio-economic drought
Economic goods depends on fresh water supply e.g. fish, hydroelectric power, foods and tap water. Drought will have socio-economic impact once a deficit in (fresh) water is not able to fulfil the demand of water to harvest or produce these type of goods anymore. This type of drought can incorporate many features of the types of drought above.

Agricultural drought
Agricultural drought is a type of drought that has an impact on agricultural activities e.g. crop loss or yield loss. This type of drought is often the result of a period of declining soil moisture, which does not meet the requirements of the crops anymore. Which can be (and often is) a result of sustaining meteorological drought. However, a plants requirements for water differ per specie, growth stage, soil type, and meteorological conditions. For example, a plant that is deeply rooted will be able to subtract water from the soil more deeply than a young and shallow rooted plant. This also means that agricultural drought can be the result of wrongdoing by human action. Such as excessive use of high yielding seeds (which require more water) or the use of water intensive crops i.e. a wrong cropping pattern. Often economic loss is used to quantify the impact of drought to the agricultural sector (Jeuken et al., 2012).

Ecological drought
The United States Geological Survey (USGS) defines Ecological drought as loss of ecosystem services. Ecological drought is similar to agricultural drought, but this time the impact is not on agricultural activities but on ecosystems. This can be loss of plants and trees, but also fish mortality as a result of declining oxygen in rivers and lakes.

2.1.5 Drought in the Netherlands

Drought might not be the first thing one thinks of when looking at the Netherlands, whereas the Dutch have a long history and relationship with water. But the concept of drought is not new either. Concerns for the effects of drought on the longer term dates back to 1988. RIVM (1988) published their report about environmental outlooks for the Netherlands: "Zorgen voor Morgen" (in English: Concerns for Tomorrow). This report covers similar concerns on the effects of drought as today's concerns, and already introduces source and effect-based measures to tackle this problem on the long run. Even though these concrete goals, concrete actions are lacking in following years after the publication (Didde, 2021).

Public Works and Water Management (in Dutch: Rijkswaterstaat) consider the months from April to September as the drought season. Within this season the daily differences in Makkink's reference evaporation (Makkink, 1957) and precipitation are measured and documented cumulatively per season (Figure 2). For the past three years, this deficit was larger than on average. Additionally, the season of 2018 was categorized as extremely dry. This is remarkable as the total yearly precipitation in the Netherlands has increased over the past decades (Figure 3). This increase in yearly precipitation is partly fueled by the increase in extreme precipitation events (Eden et al., 2018).

The water system in the Netherlands is highly controlled with the help of pumps, sluices and weirs. All water flowing in via the Rhine river at Lobith can be directed to various parts in the Netherlands (e.g. IJsselmeer or Haringvliet). In times of drought this requires deliberate choice where water will flow to, whereas "water level follows function". A certain discharge is required for the Rhine river to host its vessels for transport. The agricultural sector requires fresh water for irrigation and salinization in coastal areas has to be prevented. The National Coordination Committee for Water Allocation (LCW) is the governing body for these choices on behalf of parties as e.g. regional water authorities, Public Works and Water Management and drinking water companies. There are four categories within the displacement series of water use in order of decreasing priority: Category one prioritizes large risk entities (e.g. the stability of water retaining structures, preventing soil subsidence and preventing irreversible environmental damages), category four covers smaller risk entities (e.g. maritime transport, agriculture and industry) (Rijkswaterstaat and Unie van Waterschappen, 2019).

With the additional increase in population, the demand for fresh water, and the trend within the agricultural sector to more capital intensive crops the stress on fresh water increases. Furthermore, the climate is changing, there is an increase in extreme rainfall events and rising sea level hitherto. As of this increasing stress on fresh water and recent drought years a new consortium is brought into life called: "Extreme droughts in the Dutch water sector: Impacts and adaptation" (Smit, 2021). This consortium will inventory the effects of extreme drought for the Netherlands.

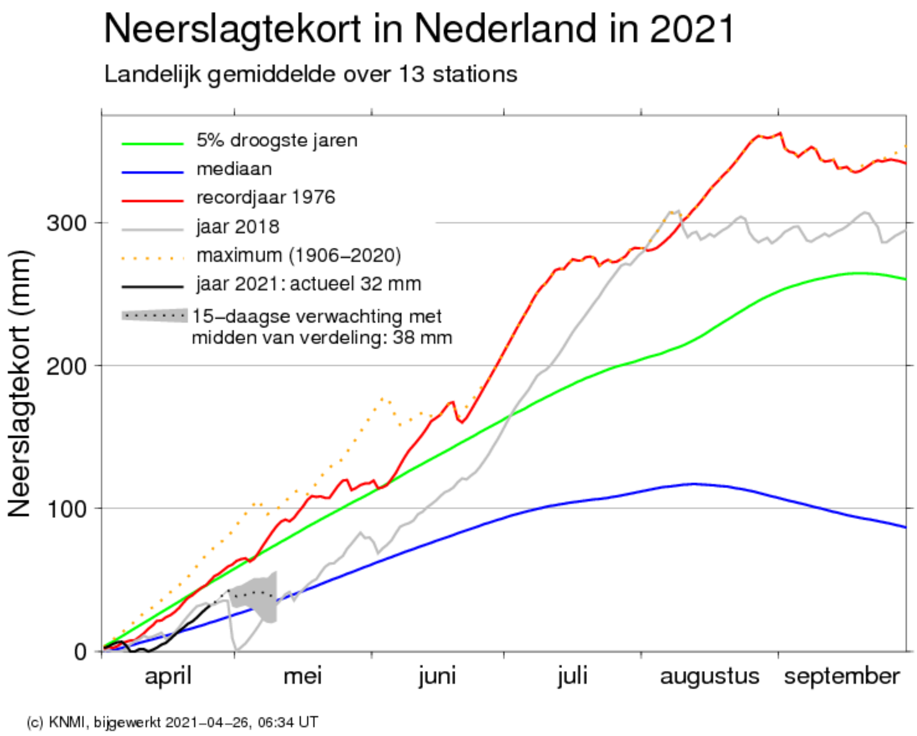


Figure 2: Precipitation deficit of national average for 13 measurement stations for the Netherlands on 26-04-2021. Plot shows the precipitation shortage of the average of the top 5% years of years 1906-2019 (green), the median of the of years 1906-2019 (blue), the record year 1976 (red), year of 2018 (grey) and current year (black). From https://www.knmi.nl/nederland-nu/klimatologie/geografische-overzichten/neerslagtekort_droogte

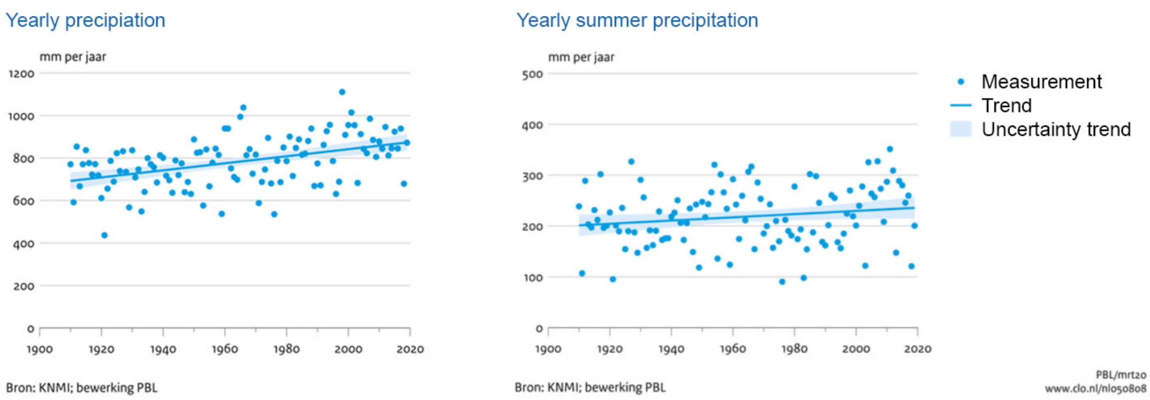


Figure 3: Total amount of precipitation in the Netherlands per year (Left) and total summer precipitation in the Netherlands per year (Right). For both yearly and summerly total amounts are increasing in the Netherlands over the past decades. From https://www.clo.nl/indicatoren/nl0508-jaarlijkse-hoeveelheid-neerslag-in-nederland

2.2 Floods

2.2.1 Introduction on floods

Similar to drought, floods are a natural disaster. In fact, they are the type of natural disaster with the largest socio-economic impact (Jonkman, 2005; MunichRe, 2007), and apart from the ice sheets, floods are quasi-total present around the world (Vinet, 2011). The European Union (2007) defines a flood as a temporary covering of a certain area by water that is normally not covered by water. This can be floods from rivers, sea or extreme precipitation, but may exclude floods from sewerage systems. Not all floods are disastrous events (e.g. from 100-year or larger return period events), whereas the more frequent floods are from small-magnitude events resulting in so called nuisance floods. These floods are characterized by low levels of inundations which do not threaten public safety, do not result in great damage propagation and create minor disruptions for e.g. routine activites (Moftakhari et al., 2018).

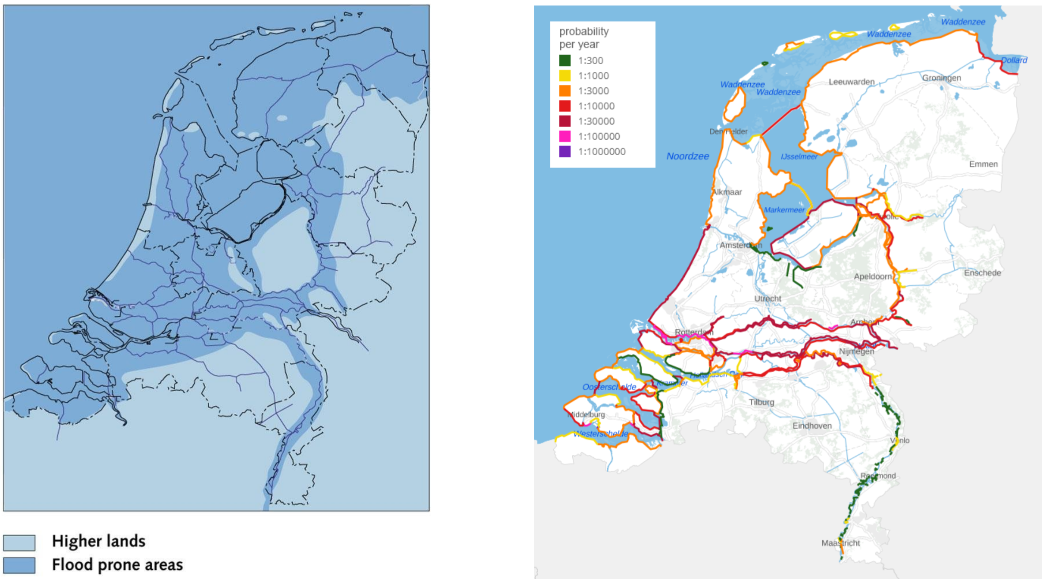
To create understanding of the types of flood based on its physical drivers, one can create causative classifications of floods based on the origin of the volume of water. Vojinovic and Huang (2015) distinguish five types of floods: fluvial or riverine flooding, coastal flooding, flash flooding, ground-water flooding and pluvial flooding. Whereas the Federal Emergency Management Agency (1999) distinguishes four types of floods: Flash floods, Coastal flooding, river and stream flooding and closed-basin flooding. It can be deduced that floods originate from multiple sources, on its own or combinations of these sources:

- Precipitation, e.g. large amounts of rain can result in flash floods
- Rivers, e.g. precipitation alone or combined with snow melt can result in extreme volumes of water larger than the discharging and storage capacity of a water system.
- Sea, e.g. a storm surge resulting in set up above normal tide levels and additional wave activity.
- Ground water, e.g. after longer periods of sustained precipitation water can increase ground water levels and/or flow through aquifers towards lower lying areas.
- Water storage basins, e.g. a dam breaks.

2.2.2 Flood (safety) in the Netherlands

Since the Middle Ages flood protections have been a prerequisite for settlement in low-lying areas in the Netherlands. During these centuries, defensive strategies were required as of the rising sea level and subsiding (peat) soils. Temporal flooding were part of life for those living in the flood prone areas. In more recent years, additional flood defence measures were realised in response to the 1953 flood disaster. Large scale measures were implemented nation wide and the Delta Committee was put into practice. This committee set new standards for flood protection which were based on cost-benefit analyses of each single dike ring by weighing the costs of the reinforcement measure against the reduction of flood risk achieved by the reinforcement measure. Little knowledge was available on flood defence bursts, so the approach for flood defence failure was based on normative water levels. These standards were used for decades, however not impeccable for riverine floods in more rural areas. In December 1993 and January 1995, two flood disasters happened in Limburg as a result of river bank overflow along the Meuse river. Though being of smaller scale when compared to the 1953 floods and no casualties were reported, these floods had significant impact on the for riverine flood risk perception.

Up until today, flood prevention is the dominant strategy in the Netherlands (Hegger et al., 2014). Flood risks have been reduced by a flood defence system consisting of (storm surge) barriers, dunes and embankments. A strategy high on the agenda, because the country is located in a low-lying delta with an extensive coastline and a large number of rivers, canals and lakes; an approximate of 55% of the Netherlands is prone to flooding whereof 29% at risk due to river flooding and 26% at risk from sea as it is below sea level (Figure 4a). Also in the Netherlands there is an increase in population over the past decades, with a resulting urbanisation of areas below sea level. Furthermore, there is an increase in extreme rainfall events and rising sea level due to a changing climate. If flood defences remain unchanged, the flood impacts will increase as a result in increased loads and exposure. The 2017, new flood protection standards were adopted to safeguard these risks (Stichting Toegepast Onderzoek Waterbeheer, 2019).



(a) (b)

Figure 4: Left, the flood prone areas in the Netherlands covering approximately 55% of the Netherlands. Right, flood safety standards from 2017 - present. Presented probabilities are the flooding probabilities (various colors) per embankment trajectory (each single continuous and colored line) per year. From `www.pbl.nl`.

The new 2017 flood protection standards are anchored in the Dutch law, Water Act (Figure 4b). One of the important changes is the replacement of the design water levels for embankments by a more comprehensive flooding probability. The design water level translates to the probability of exceedance of a set water level at a water retaining structure. Whereas the flooding probability translates to the probability of losing the water retaining capacity for a dike trajectory, thus including the probability of exceedance of a set water level and breaching.

The new standards were based on three criteria: efficiency, equity and societal disruption. To account for equity, a minimum flood protection level was defined as the probability to die due to a flood event, i.e., Local Individual Risk (LIR). Every single individual in the Netherlands who is situated behind a primary flood defence has at least a level of protection of the LIR. This probability for loss of life as a consequence of flooding defines at a maximum 1/100.000 per year. Additional protection is applied to embankment stretches where failure may result in large number of fatalities or large economic damages and/or damage to or failure of vital and vulnerable infrastructure.

2.3 Risk

2.3.1 Risk (Management)

Nowadays the risk is often defined as the probability of an unwanted event to occur multiplied by the consequences or losses (see next section: various definitions on Risk and related terms). This risk can be calculated deterministically, by the analysis of scenarios and adding up these risks to create a total risk profile or probabilistically, which is based on all (known) unwanted events. The use of one or the other method is case-dependent and both methods are supplementary to the other.

In the Netherlands, flood risk is managed on the basis of a risk approach. To perform a successful risk assessment for risk management, one first has to set the scope and objectives of the analysis (i.e. system definition), investigate what undesired events are possible (i.e. qualitative analysis) and then quantify the risk of these events (i.e. quantitative analysis) (Jonkman et al., 2016). At last, the administered risk has to be evaluated on wether it is acceptable or not (Figure 5).

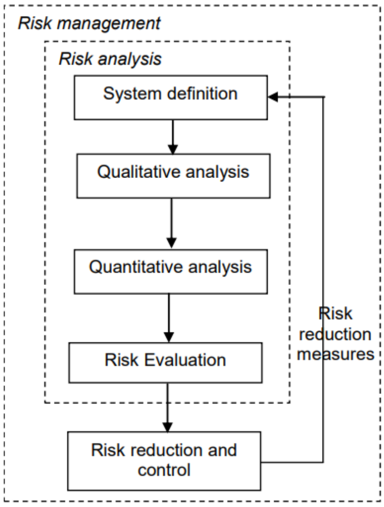


Figure 5: Schematization of the risk cycle in risk analysis and risk management. From Jonkman et al. (2016, p. 61)

2.3.2 Compound (multiple) events

Traditionally, risk analysts focus on the extremes of a univariate random variable or process (e.g. drought, precipitation). However, hydro-climatic variables are often interrelated, which means that focusing on a single random variable can be a oversimplification from reality and it could lead to incomprehensive risk analysis (Hao et al., 2018). It is essential to look at the interaction between these variables (i.e. the multiple events). This research will focus on this type of events, with a primary focus on cascading hazards. The IPCC (2012) defines compound events as:

> *"Compound events can be (1) two or more extreme events occurring simultaneously or successively, (2) combinations of extreme events with underlying conditions that amplify the impact of the events, or (3) combinations of events that are not themselves extremes but lead to an extreme event or impact when combined."*

Given this definition, cascading hazards can be considered within the domain of compound hazards. Whereas cascading hazards can be the result of one or more simultaneous hazard triggering a single subsequent or multiple subsequent hazards. Visualization of such cascading hazard is presented in figure 6.

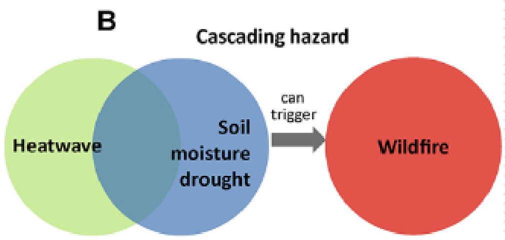


Figure 6: Visual interpretation of cascading hazards. From de Brito (2021)

2.3.3 Definitions of risk and related terms

Remark: These definitions are copied as is and can be skipped for now (Zscheischler et al., 2018). This will be changed and supplemented later on. If you have any recommendations on additional elements, please let me know.

Risk. The "effect of uncertainty on objectives". According to the IPCC96, risk is the potential for consequences when something of value is at stake and the outcome is uncertain, recognizing the diversity of values. Risks arise from the interaction between hazard, vulnerability and exposure and can be described by the formula:

> *Risk = (probability of events or trends)* $\times$ *consequences*

where consequences are a function of the intensity of hazard (event or trend), exposure and vulnerability. Here, we use the term risk to refer to environmental and societal impacts from weather and/or climate events.

Exposure. The presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected.

Vulnerability. The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

Hazard. The potential occurrence of a natural or human induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources96. Here, the term hazard usually refers to climate-related physical events or their physical impacts.

Drivers. These include climate and weather processes, variables and phenomena. We refer to the term drivers throughout as direct (climate and weather related) causes of climate-related hazards.

Impacts. The effects of physical events on natural and human systems

2.4 Case study

To better characterize how drought events can exacerbate the risk of flooding, the failure of the dike at Wilnis in 2003 will be investigated. In this section a short introduction to the Wilnis case is described.

2.4.1 Dike failure at Wilnis

The summer of 2003 was very dry and warm; multiple meteorological records were broken in De Bilt. During the night from 25th to 26th of August in 2003 a dike segment of 60 meters slided in Wilnis. Water flowed in from the ring canal and streets were flooded, resulting in power cuts and the need to evacuate over 1500 people. To solve the flooding the canal was temporarily sealed off on both side of the breach.

Like many small dikes in the Netherlands, this dike was made out of peat. This material is affected by dry weather, whereas the drying out of peat results in cracks, tears and a lower specific weight. This can result in sliding (a part) of the dike, as seen in Wilnis in 2003.

(a)

(b)

Figure 7: Left, aerial picture of the dike segment slide in Wilnis of 2003. On the right, the location of Wilnis in the Netherlands is indicated.

3 Thesis planning

For a master thesis for Civil Engineering at the TU Delft a number of 28 weeks should be reserved (40 ECTS = 1120 hours). This thesis started on the 14th of April, which means its theoretical end date is at the 21st of October. Given general expected delays for a master thesis and midterm summer vacations, this final date will expected later on. This will mean that the thesis will have a practical deadline end of 2021 (Figure 8). Respecting the thesis committee and thesis student their time off during summer vacations, this final deadline can be discussed later on during one of the committee meetings.

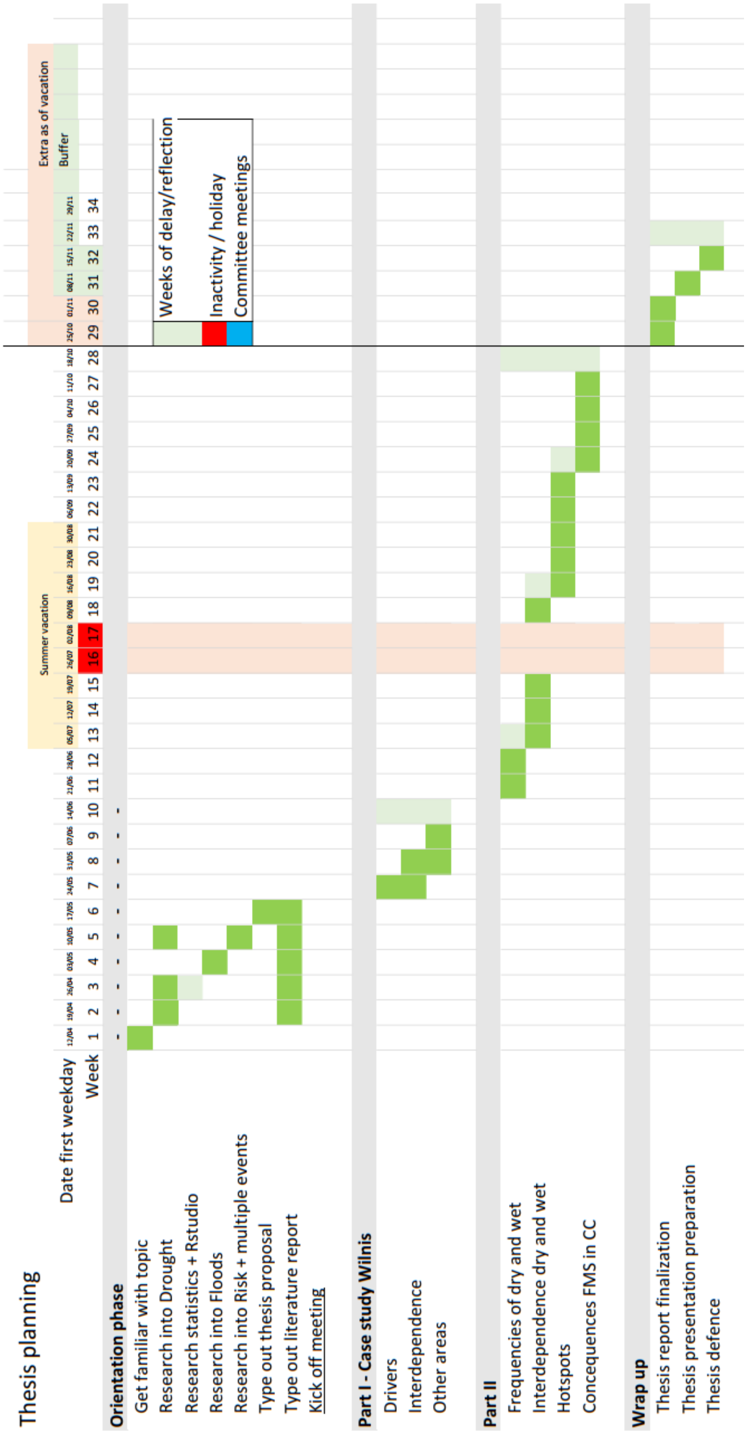


Figure 8: Gantt chart for thesis

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A Appendix A : Literature research methodology

In this appendix the strategy for performing the literature study and its related activities are described.

A.1 Research strategy

A research strategy provides structure for conduction a research study. The TU Delft Library (2021) offers guidelines on information literacy, which can be used for a literature study. These guidelines are divided into the following sections:

- Searching and Resources
- Managing your information
- Writing and Publishing

The rest of this chapter will elaborate on these sections and its application.

A.2 Searching and resources

A search plan was created to expedite the search for relevant literature. Questions to be answered during this literature study were:

On drought:

- How can we define drought?
- What are the drivers and indicators for drought?
- How relevant is an analysis of drought in the Netherlands?

On floods:

- How can we define floods?
- What are the drivers or indicators for floods?
- How relevant is an analysis of floods in the Netherlands?

On risk and cascading hazards:

- What is understood by risk?
- What is understood by cascading hazards?
- What happened in regards to the dike slide in Wilnis of 2003?

First, all research papers provided by Ms Ragno (daily supervisor) were scanned or read thoroughly. Some of these were key papers, which could be used as a stepping stone to other relevant literature. This was done by performing citation searching (i.e. looking at papers that cite the key paper) or by applying the snowball method (i.e. looking for papers from the same author, looking for papers by using all or some of the same keywords and looking at the references of the key paper) (TU Delft Library, 2021).

Additionally, the use of search engines was included to comprehend more general results to the literature study. A good search starts with the correct keyword or combination of keywords. A non-exhaustive list of keywords for this literature study is presented in Table 1. These keywords were used in available search engines beginning with highest priority: Scopus, Web of Science, TU Delft library, Google Scholar and Google. When applicable, the use of search operators was included.

Table 1: Non-exhaustive list of keywords used for additional literature search

Main topic related terms	Cascading hazards Flood management practices OR flood risk management OR FRM Climate change OR Climate extreme Drought Drought indicators Flood Precipitation
Secondary topic related terms	Compound hazards OR extremes OR events Risk Impact Consecutive dry and wet periods Wilnis dike OR embankment AND burst OR breach OR slide Complex disasters OR events Multivariate extremes OR events Conjoint events OR extremes Domino OR domino effect
Constraints	The Netherlands Date e.g. past 20 years or dry years like 1976, 2018, 2019, 2020 and years of flooding events

A.3 Managing your information

The management of information can be divided into the categories of data storage, communication and reporting. Further elaboration per category follows.

Data storage

All data, currently mostly consisting of research papers, is stored on a local hard disk synced with the cloud storage service Microsoft Onedrive (Microsoft, 2021a). Additional back-ups are created on the cloud storage service TransIP Stackstorage (TransIP B.V, 2021). This last mentioned cloud storage lends itself perfectly for large file sharing through a hyperlink in e-mails.

Communication

Communication with the daily supervisor is done through Microsoft Teams. Microsoft Onedrive (Microsoft, 2021a) is integrated with Microsoft Teams (Microsoft, 2021b) for the convenience of file sharing. Communications to the rest of the thesis committee is done by e-mail and a virtual meeting platform of choice. Additional file sharing will be done through one of the above mentioned cloud services.

Reporting

Writing the report is done in Overleaf with an integrated Reference Management Software (RMS). The RMS used for this thesis is Mendeley (Elsevier B.V., 2021). This software functions as an additional storage of all used research papers.

A.4 Writing and publishing

Writing and publishing relates to how information is documented. When writing a scientific paper it is expected to take into account the aspects of copyright and perform citations correctly. The expected outputs for this thesis are a thesis report, a peer-reviewed publication and a final presentation. The thesis report will be in line with this thesis proposal. All requirements for the peer-reviewed publication will be assorted later on during the study.

B Appendix B: Drought schematization

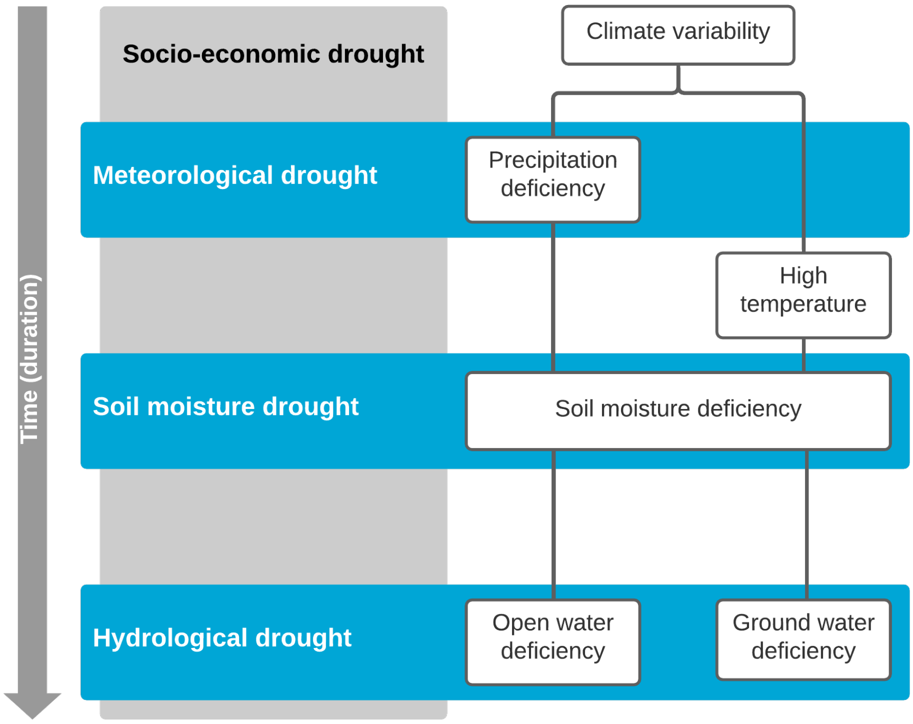

Figure 9: Drought definitions diagram. By author