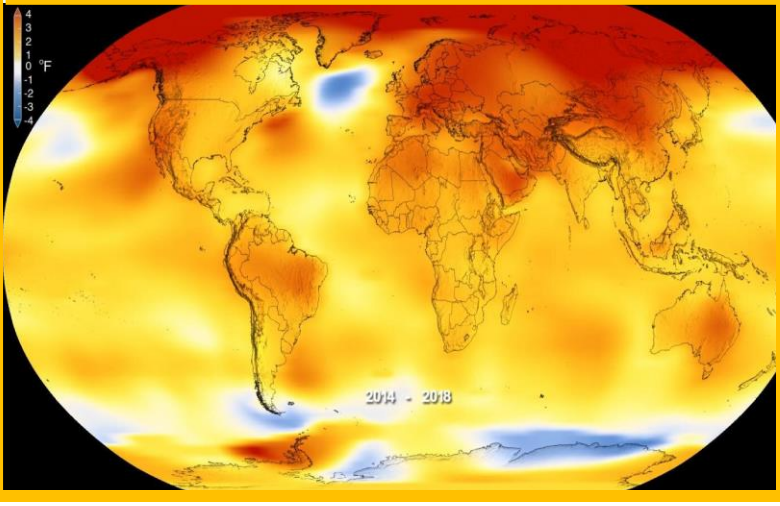
Master Thesis- master Water Science and Management
28-07-2019

Combining severe drought and heat experiences from the Netherlands and New Orleans attempting to create a more climate resilient delta in the future



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Deltares
Enabling Delta Life

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Summary

The world is becoming warmer due to climate change and will warm up another 2-3 °C at the end of this century. As a result, weather patterns become more extreme globally, with more intense precipitation events, more extreme heat and longer periods of meteorological drought. While extreme precipitation has direct and visible impacts on society, drought impacts are often dormant and related damages could appear months later. At this moment, research to the impacts of drought and heat in urban areas is limited. In the Netherlands, there has been more attention lately due to the impacts of severe drought in the summer of 2018. In addition, the current summer broke already national temperature records of 40,7°C (25-07-2019).

It is expected that drought and heat and their related impacts will appear more often in the future. Therefore, this thesis studied the appearance of meteorological drought, hydrological drought, heat waves and their related impacts from the past thousand and hundred years in urban areas of the Netherlands and for the city New Orleans. Even though the climate in New Orleans is different from the Netherlands with almost twice as much annual rainfall, with +10 °C higher average summer temperatures and higher humidity levels it is still interesting to study these two areas because both are located in large delta areas, they are below sea level and both are vulnerable for land subsidence and climate change.

In the Netherland, meteorological drought can appear for several consecutive months. Moreover, meteorological drought is often aggravated with hydrological drought. The driest year is 1976 with a precipitation deficit of 361 millimeter and a PDSI value of -7. Recent extreme drought appeared in 2003 and 2018. In these years' temperatures were above average and there fell half or even less precipitation compared to an average year. New Orleans experiences drought periods differently. Meteorological drought is often interrupted by extreme rainfall events which leads among others to street flooding. Nevertheless, in 1976, the precipitation deficit was 636 millimeters which is almost double as high as the driest year of the Netherlands. The most recent extreme drought appeared in 2000 (PDSI -6,2), 2006 and 2011. Furthermore, hydrological drought is not always combined with low Mississippi discharges.

In both areas drought and heat are often compound events. However, heatwaves are more extreme and appear more frequently in New Orleans. Nevertheless, drought and heat related impacts causing large damages, economical losses and poses a human health threat. In this study, these consequences are summarized for infrastructure (above and below surface), housing, levees, nature (surface water, vegetation, animals), industry and human health.

Meanwhile, in the Netherlands drought damages are caused due to the combination of meteorological and hydrological drought. In New Orleans most damages are not caused by meteorological drought but by large groundwater level varieties due to drainage of the sewage system and storm drainage pipes and due to seasonally varieties of precipitation which results in two types of subsidence (differential subsidence and shrink and swell).

The Netherlands and New Orleans are traditionally focused to transport a water surplus as fast as possible out of the system into the ocean for the prevention of flooding. However, due to future increase of drought and heat events the government should implement measures to retain water during wet periods. This prevents the risk on fresh water shortage during drought but also keeping groundwater levels high, prevents for further land subsidence and salinization. To mitigate the impacts of heat, cities have also to reduce the urban heat island effect. In general, this can be done by planting more trees and implement other green and blue infrastructure measures in the city planning. In addition, the design of new built houses should be heat repellent.

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1. Introduction

According to the United Nations (UN), climate change is now affecting every country on every continent (United Nations, 2015). Without action, the global temperature increase could surpass 3°C this century as a result of human induced climate change. The consequences of the temperature rise are already visible by changing weather patterns, rising sea levels and an increase in extreme weather events (United Nations, 2015). These extreme events result in flooding, droughts and famines all over the world (Vidal, 2017). To reduce the effects of climate change, the Paris Agreement was adopted at the Conference of the Parties (COP21) in Paris on 12 December 2015. This agreement stands that all countries strengthen their forces to limit the global temperature rise below 2 °C (United Nations, 2018). Nevertheless, the future is uncertain and therefore it is necessary to make vulnerable areas more resilient to climate change.

1.1 Climate change impact in New Orleans

One of the areas particularly affected by human induced climate change is New Orleans. The city is located at the southeast of the US and is a vulnerable area for climate change effects through the remainder of the 21st century (Schleifstein, 2018). The city was widely discussed after the area was hit hard by hurricane Katrina in 2005. Katrina caused 108 billion US dollars of damage, about 1,800 people had lost their lives and more than 800,000 houses were damaged or destroyed in the storm (Hamlin, 2018). The extreme storm exposed the vulnerability of the city and low-lying parts flooded. At present day, New Orleans is not completely recovered from the natural hazard. Flooding is partly caused by the fast subsidence rate of the area (Nasa, 2016). Almost 50% of the city is already below sea level with a maximum depth of 2.44 meter (8 feet) and subsides by several millimetres annually (WorldAtlas, 2018). As a result of further land subsidence, future sea level rise and the intensification of rainfall caused by climate change, New Orleans will continue to face more challenges. In addition, heatwaves and drought events may occur more often and become more intense (Carter et al., 2014). This will affect the liveability in urban areas (EPA. 2017).

1.2 Climate change and drought

Earlier research indicates an increase in global severity, frequency and trends of hydrological drought at the end of the 21st century (Wanders et al., 2015; Prudhomme et al., 2014; Spinoni et al., 2013). The National Oceanic and Atmospheric Administration has designed an Advanced High-Resolution Radiometer- (AVHRR) based on Vegetation Condition Index (VCI) and Temperature Condition Index (TCI) for detecting and monitoring large areas on drought-related vegetation stress (Kogan, 1997). Droughts in the US are monitored and are predicted several months in advance using the model-based Drought Monitoring and Prediction System (DMAPS, Tadesse et al., 2005). This provides valuable information for drought preparation and drought impact assessment at national and local scales (Tadesse et al., 2005). A similar monitor has been developed in Europe for monitoring, assessing and forecasting drought across the European Continent (Vogt et al., 2011; EDO, 2019)

In the US, several studies have been done to the impact of drought. This conducted the impacts of forest biodiversity, structure and fires (Marlon et al., 2012; Clark et al., 2016). Other studies are about the river dynamics, river systems and the crop yield (McKee et al., 2004; Lobell & Field, 2007). The European Drought centre has like the US, a database for collecting all kind of drought impacts (European Drought Centre, 2012). Still, it is not a complete overview. Especially drought impacts at local scale in urban areas are less analysed.

Since 2007, there are several projects to make New Orleans climate-robust. Most research is to reduce the risk of flooding. After hurricane Katrina, the Dutch Dialogues played an important role to bring multiple disciplines together to make New Orleans more resilient against natural disasters (Nemes, 2018). In 2008, two separate Dutch Dialogues Workshops took place. In these workshops' Dutch engineers, urban designers, landscape architects, city planners, and soils/hydrology experts and their Louisiana counterparts worked together and exchanged information about water issues and mitigation options for New Orleans (Nemes, 2018). As a result, the Greater New Orleans Urban Water Plan was set up in 2011. This plan developed sustainable strategies for managing the water resources around New Orleans. The focus was on three basic issues: flooding caused by heavy rainfall, subsidence caused by the pumping of stormwater, and wasted water assets (Urban Water Plan, 2018). Recently, New Orleans received $ 141.3 million from the US Department of Housing and Urban Development for their plan 'Reshaping the Urban Delta', to increase the resistance for natural hazards in Gentilly (Deltares, 2018b).

The research to drought and heat at local scale are limited in New Orleans. In the Netherlands, the effects of extreme dry periods have been analysed. Extreme droughts occurred among others in the summers of 1976, 2003 and 2018. These droughts and the related impacts are described in several reports written by Rijkswaterstaat (executive agency of the Ministry of Infrastructure and Water Management in the Netherlands), newspapers and water boards (Rijkswaterstaat, 1976). Furthermore, the research framework ''kennis voor klimaat'' analysed the consequences of extreme dry periods in urban areas (Deltares, 2015).

The research to compare the appearance and experiences of drought and heat event in the Netherlands and New Orleans will be interesting because both areas are located in major river deltas of, respectively the Rhine and the Mississippi, whereof a large part of the land is located below sea level, the soil is built up from soft ground and both areas are polders.

1.3 Aim

The aim of this work is to analyse to what extent the Netherlands and New Orleans could exchange experiences in extreme drought and heat events to obtain new insights in drought and heat related impacts and possible mitigation options. Currently, the effects of drought and heat at local scale in New Orleans is underexposed. However, both study areas will experience more extreme heat and drought events caused by future climate change, especially in the summer months (Dai, 2013). Therefore, it is important to bring up and analyse the consequences of these events. Furthermore, this study attempts to raise the awareness of the importance of drought and heat analyses to prevent future impacts caused by drought and heat in urban areas.

The objective of this research is: to analyse drought and heat and the severity of compound drought and heat over New Orleans and the Netherlands. The study started by doing research to drought and heat trends from the past 1000 years. After that, I will analyse the occurrence and the meteorological characteristics of drought and heat events in more detail for the Netherlands and New Orleans over the past 100 years. Furthermore, this part describes the relation between these two events whether drought and heatwaves are compound events and investigates which socio-economic impacts will occur during and after extreme heat and drought. Moreover, it should be clear at which intensity of drought and heat a certain impact will occur. After that, this study provides predictions how drought and heat events will change in the future in both areas. Besides, the relationship of the discharge of the Rhine river and the Mississippi with drought will be analysed. The final objective of this master thesis is to provide recommendations of which measures can be taken to prevent New Orleans for the risks of extreme drought and heat in the future. Therefore, the following research questions have been made.

Research question:

What are the socio-economic impacts of drought and heat events in the Netherlands and in New Orleans, what are the differences and similarities of the occurrence and impacts of drought and heat between the two areas and what are the tools for drought mitigation?

Sub questions:

1) What are the meteorological and hydrological characteristics of drought and heat over the past hundred years, are they compound events and how will drought and heat change in the Netherlands and in New Orleans in the future?
2) To what extent correlates low Rhine and Mississippi discharges with drought and heat events?
3) What are the socio-economic impacts of drought and heat, are these impacts different in the Netherlands and in New Orleans and when do these impacts occur?
4) What mitigation options are available to reduce drought impact in the Netherlands and in New Orleans?

1.4 Thesis structure

The theory of drought and heat plus the future expectation will be discussed first (chapter 2). How the research was set up, is written in the methods section (chapter 3). After that, the background provides the general meteorological and hydrological information respectively from the past thousand and 100 years (chapter 3.2). Subsequently the results of drought and heat in the Netherlands and New Orleans are presented just as the relation between drought and Rhine- and Mississippi discharges (chapter 4). Furthermore, the drought and heat related impacts in the study areas are described in chapter 5 and 6. After that, the possible mitigation options are written in chapter 7. This will be followed with a discussion about the reliability of the data plus the similarities and the differences of drought and heat impacts for the two study areas (Chapter 8). At the end, the main conclusion of this master thesis will be provided.

2. Theory

2.1 Drought

Drought is caused by below average water availability and can occur in all parts of the hydrological cycle. Moreover, drought is not just a precipitation deficit but arises from a complex interplay between natural precipitation deficiencies, the human water demand and the environmental water use (Quiring, 2015). The intensity of drought depends among other on the evaporative demand which is mainly driven by the presence of vegetation. How much water will be evaporated depends on the amount of incoming sun radiation, wind, temperature, pressure, humidity, cloud cover and the ground wetness. Relatively dry air and strong winds will increase the evaporation process (KNMI, 2018a). All variables are largely varying between years and even days which makes drought research difficult. Furthermore, the strength and duration of drought can be increased due to the effect of heat on air temperature and thus evaporative demands. However, drought and heat have different effects on the environment, where drought primarily effect the water availability, heatwaves only impact the air temperature. Moreover, drought is divided concerning type and duration in: meteorological, agricultural and hydrological drought (Figure 2.1).

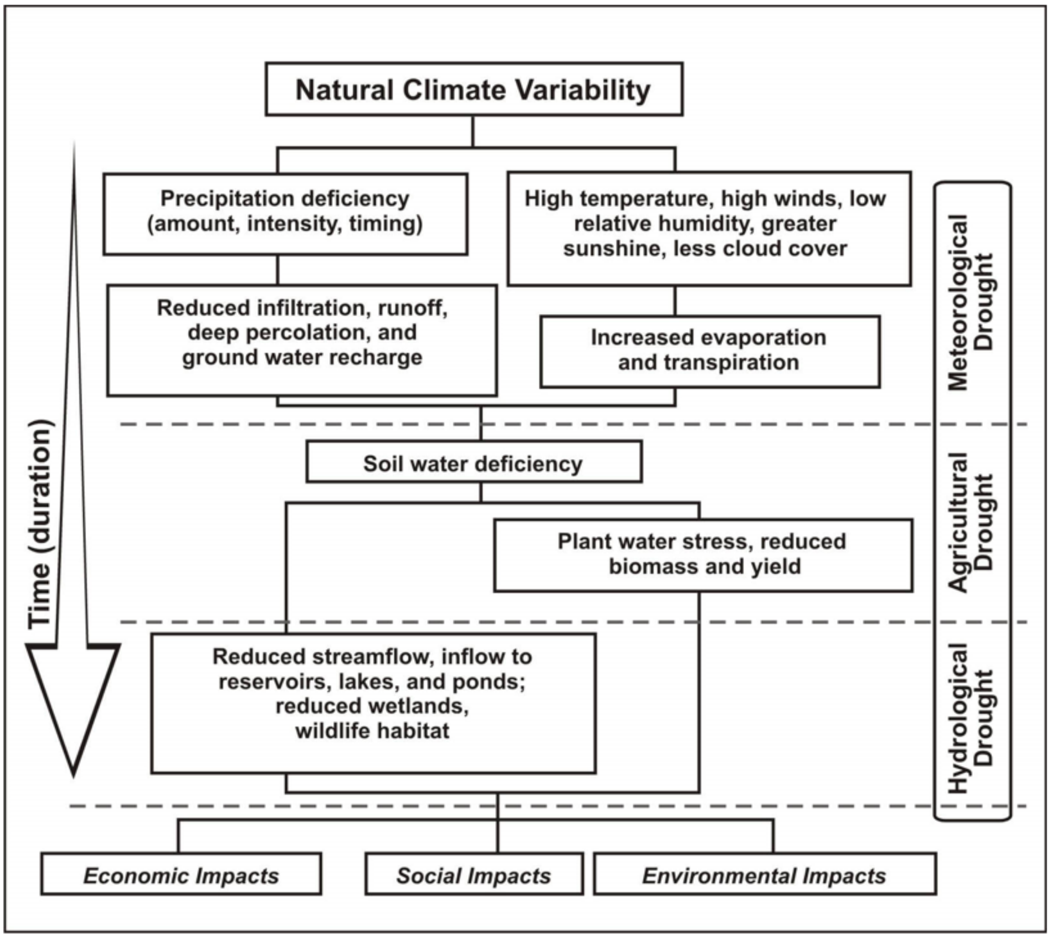


Figure 2.1: Relationship between the type and duration of drought. Source: (Quiring, 2015)

2.1.1 Meteorological drought

The main characteristic of meteorological drought is dependent of the degree of dryness and the duration. Besides, the definition is region-specific. This, because deficiencies of precipitation are reliant on specific atmospheric conditions in the different climate regimes. Most meteorological drought definitions relate actual precipitation departures to average amounts on monthly, seasonal, water year, or annual time scales (Quiring, 2015). In the Netherlands, meteorological drought is measured annually by The Royal Dutch weather station (KNMI).

2.1.2 Agricultural drought

If the precipitation deficit becomes extremely large and the amount of water in the soil drops to large depths than there is agricultural drought. At that moment, crops are not able to meet the needs of their moisture requirements because of the lack of water in the unsaturated zone. This affects agricultural production negatively. Besides the agricultural sector, all vegetation in nature suffers from agricultural drought (KNMI, 2018b).

2.1.3 Hydrological drought

Hydrological drought occurs when there below average water availability in rivers, lakes and aquifers. The Rhine and the Mississippi are the main fresh water suppliers for both deltas. Impacts related to hydrological drought are salinification, obstruction of river navigation, irrigation limitations and ecological aspects will be endangered. In addition, increasing water temperatures due to heatwaves in combination with low water levels results in a decline of the water quality (KNMI, 2018b). The KNMI is conducting research into the simultaneous occurrence of meteorological and hydrological drought.

2.2 Precipitation deficit

As a measure of drought, the KNMI calculates the continuous potential precipitation surplus since 2000 (Figure 3.2.7). This is obtained by calculating the difference between the amount of precipitation and the reference crop evaporation from April 1 to September 30. This period is based on the start of the growing season which is defined as the day on which the average day temperature reaches 5 ° C and no longer become less until 1 July. In addition, the calculation stops during the measurement period when the cumulated values become below zero (Sluijter et all., 2018). In the end, the daily difference is cumulated over the entire summer (KNMI, 2018b). This value is mainly usable for the agricultural sector.

2.3 PDSI and SPEI

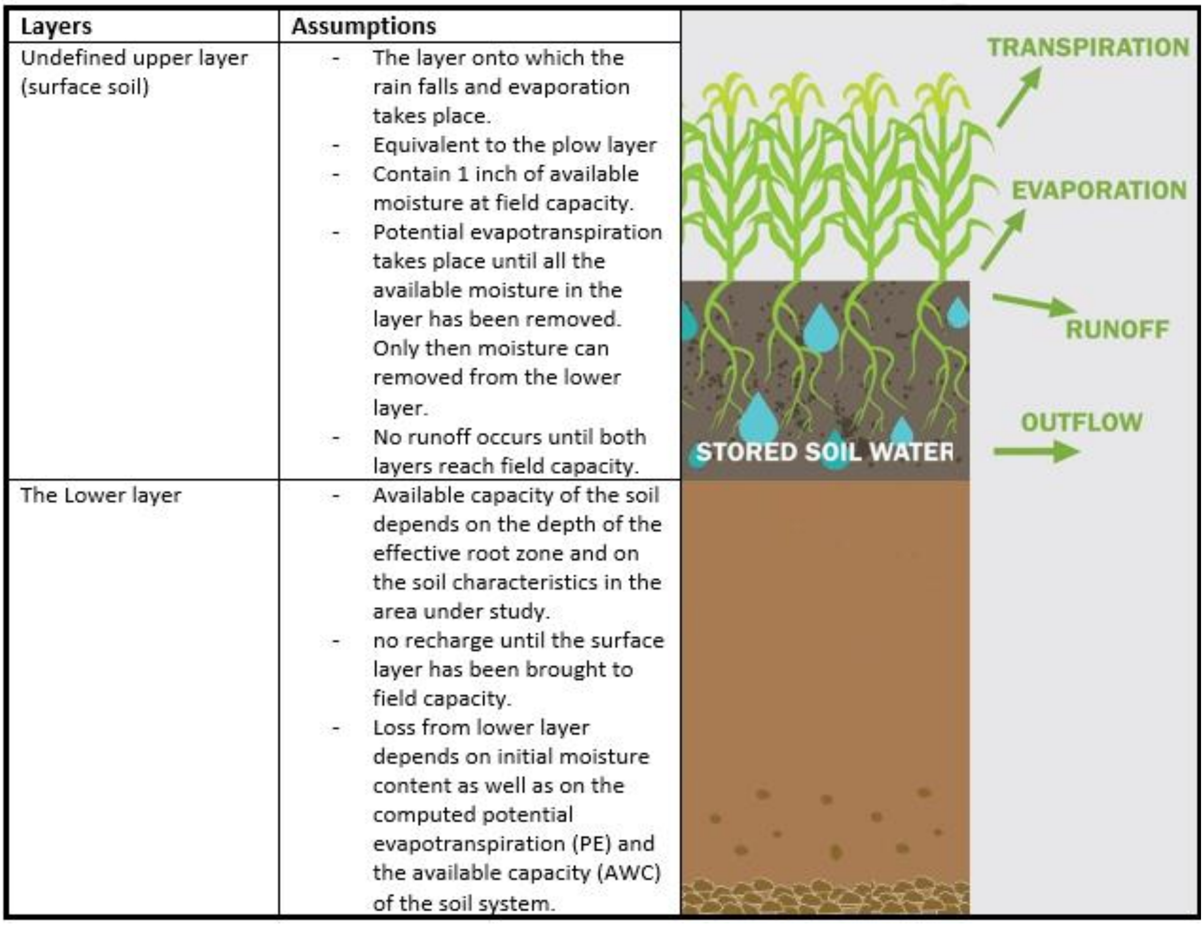
A widely used index which measures actual drought severity has been developed by Wayne Palmer in 1965 (Palmer, 1965). PDSI (Palmer drought index) is calculated by using readily accessible monthly surface air temperature and precipitation data along with the water-holding capacity of soils (based on the soil water balance equation; figure 2.2). The index varies between the -10 and +10 (Table 2.1). The model of the PDSI consist two parts. First, the hydrological index for the water exchange between the atmosphere and the soil. The second part is based on the meteorological conversion, timing the start and the end of a drought or a wet event (Annex A). The key strength of the PDSI is to determining drought from several months to years. Furthermore, the index takes global warming through potential evapotranspiration into account (Aiguo, 2017). Another index of drought is the Standardized Precipitation Evapotranspiration Index (SPEI) uses weekly or monthly values of precipitation and potential evapotranspiration to calculate the climatic water balance (table 2.2; Haslinger et al., 2014).

Table 2.1: Classes for wet and dry periods. Source: (Palmer, 1965)

Description	Palmer Drought
Extremely wet	4.0 or more
Very wet	3.0 to 3.9
Moderately wet	2.0 to 2.9
Slightly wet	1.0 to 1.9
Normal	0
Mild drought	-1.0 to -1.9
Moderate drought	-2.0 to -2.9
Severe drought	-3.0to -3.9
Extreme drougth	-4.0 to -4.9
Exceptional drought	-5.0 or less

Table 2.2: Classes for drought severity based of the SPEI. Source: (Haslinger et al., 2014)

Flood/ Drought category	SPEI values
Wet	≥ 0,5
Near Normal	-0,94 -- 0,49
Mild drought	-0,99 -- 0,50
Moderate drought	-1,49 -- 1,00
Severe drought	-1,99 -- 1,50
Extreme drought	≤ -2,0



Layers	Assumptions
Undefined upper layer (surface soil)	- The layer onto which the rain falls and evaporation takes place. - Equivalent to the plow layer - Contain 1 inch of available moisture at field capacity. - Potential evapotranspiration takes place until all the available moisture in the layer has been removed. Only then moisture can removed from the lower layer. - No runoff occurs until both layers reach field capacity.
The Lower layer	- Available capacity of the soil depends on the depth of the effective root zone and on the soil characteristics in the area under study. - no recharge until the surface layer has been brought to field capacity. - Loss from lower layer depends on initial moisture content as well as on the computed potential evapotranspiration (PE) and the available capacity (AWC) of the soil system.

Figure 2.2: Schematically version of the soil water balance including the made assumptions by Palmer used to calculate the PDSI index.

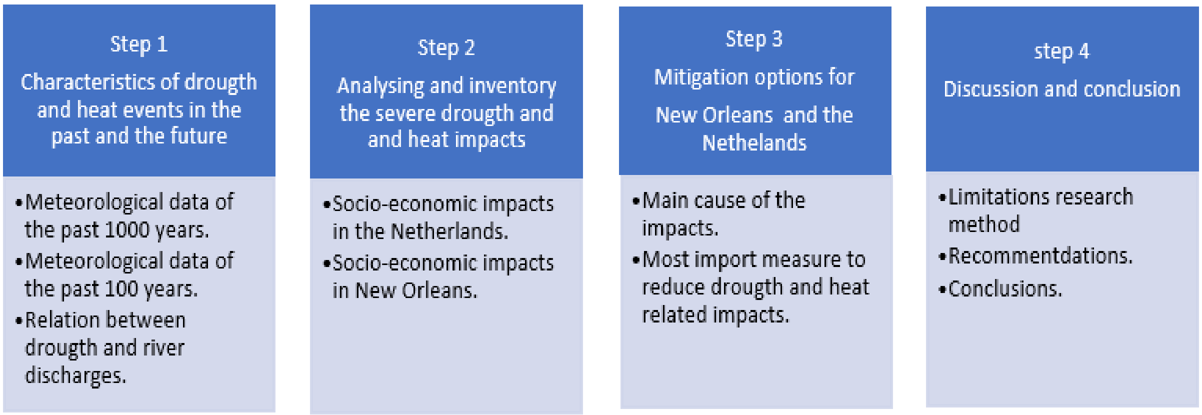
2.4 Heat waves

The KNMI describes a heatwave as the maximum temperature is 25 °C or higher for five consecutive days, of which three days are 30°C or more (tropical day). The effect of heat is strengthening in urban areas, the so-called urban heat island (EPA, 2019). This is caused by high building density, the replacement of natural surfaces with hardened and water-resistant surfaces and due to more dark surfaces with a lower albedo resulting in temperature differences of 1 and 8 °C between rural and urban areas. The urban heat island is most intense on warm, clear summer days with little wind (Döp et al., 2011).

3. Materials & methods

3.1 Research framework

The main objective of this research is to formulate recommendations which measures should been taken to make New Orleans more resilient against drought and heat. This will be conducted in several steps by combining the Dutch drought and heat experiences with the drought and heat experience of New Orleans (Figure 3.1).



Step 1

Characteristics of drougth and heat events in the past and the future

- Meteorological data of the past 1000 years.
- Meteorological data of the past 100 years.
- Relation between drougth and river discharges.

Step 2

Analysing and inventory the severe drougth and and heat impacts

- Socio-economic impacts in the Netherlands.
- Socio-economic impacts in New Orleans.

Step 3

Mitigation options for New Orleans and the Nethelands

- Main cause of the impacts.
- Most import measure to reduce drougth and heat related impacts.

step 4

Discussion and conclusion

- Limitations research method
- Recommentdations.
- Conclusions.

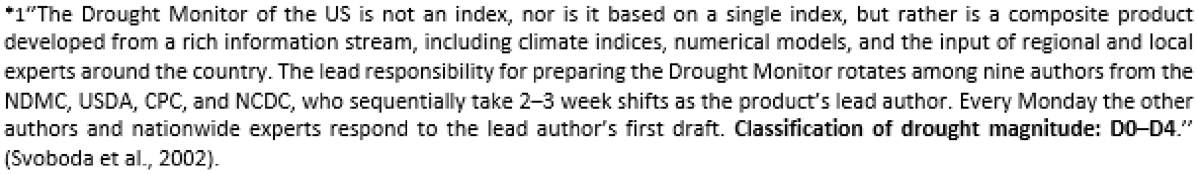
Figure 3.1: Research framework

Step 1

The first step is to analyse drought and heat periods and its impact in a historical context by reading literature about the weather of the past 1000 years written by J. Buisman (Figure 3.2). This data is visualized by creating a graph consisting of the historical temperature and the drought and heat events. The drought intensity is divided into three categories (table 3.1) and the heat intensity is an index from 1 (extremely cold) to 9 (extremely warm). Furthermore, the average annual temperature is obtained from the KNMI. Thereafter, the occurrence and characteristics of drought and heat events in the Netherlands and New Orleans of the past 100 years is analysed. Whereby, the meteorological and hydrological data is collected from datasets and reports provided by the government, weather stations and the drought monitor*1 (Svoboda et al., 2002). Besides, future drought and heat will be discussed. This data will be conducted from literature, climate scenarios produced by the KNMI (NL) and the national centre for environmental information (US), and the climate explorer.

Table 3.1: Categorized drought intensity based on the descriptions from "thousand years of weather, wind and water in the low lands" written by Buisman.

Description from Buisman	Category
Dry	1
Very dry	2
Exceptionally/ remarkably dry	3



*1"The Drought Monitor of the US is not an index, nor is it based on a single index, but rather is a composite product developed from a rich information stream, including climate indices, numerical models, and the input of regional and local experts around the country. The lead responsibility for preparing the Drought Monitor rotates among nine authors from the NDMC, USDA, CPC, and NCDC, who sequentially take 2–3 week shifts as the product's lead author. Every Monday the other authors and nationwide experts respond to the lead author's first draft. **Classification of drought magnitude: D0–D4**." (Svoboda et al., 2002).

Figure 3.2: The six books ''Thousand years of weather, wind and water in the Low lands'' written by J.Buisman.

The relation between precipitation deficit and discharge of the Rhine is already studied at Deltares (Chapter 5.3). A similar research will be done for the Mississippi at New Orleans to analyse if there is any correlation between drought and low river discharge from Tarbert Landing (Figure 3.3). This measure point is used because it has the longest continuing data of the lower Mississippi (1930 to present).

After step one, the first sub question ''What are the meteorological and hydrological characteristics of drought and heat over the past hundred years, are they compound events and how will drought and heat change in the Netherlands and in New Orleans in the future?'' and ''To what extent correlates low Rhine and Mississippi discharges with drought and heat events?'' will be answered.

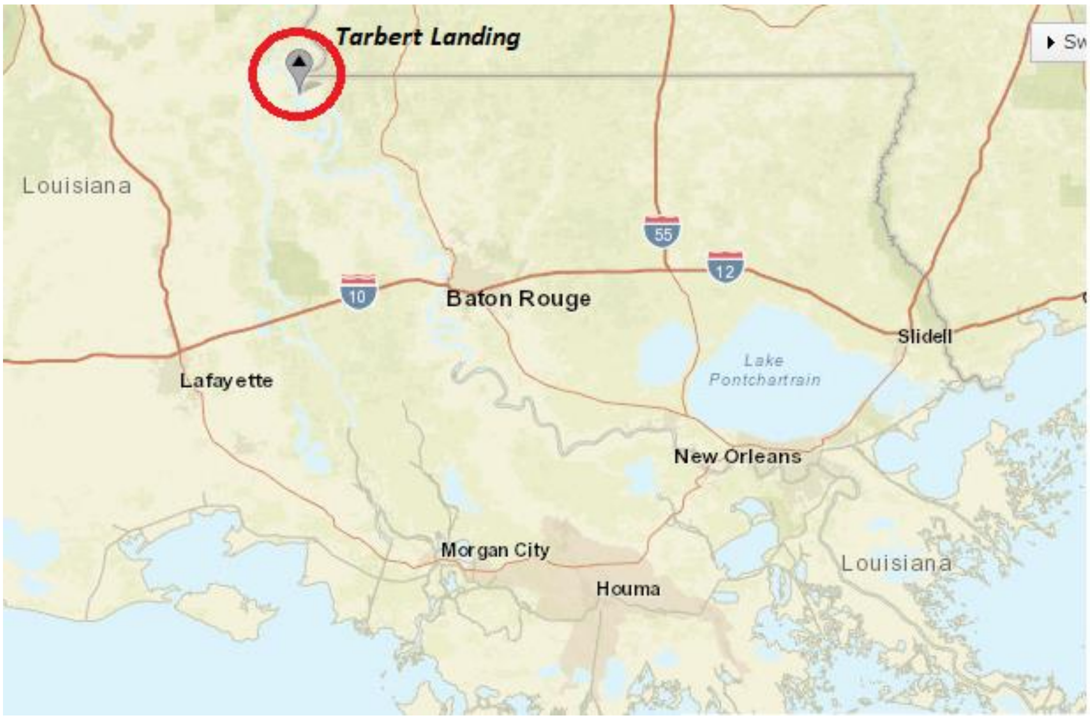


Figure 3.3: The Lower Mississippi area and the measurement location Tarbert Landing, located at 493 kilometers (306.3 mile) upstream of the Mississippi river mouth.

Step 2 & 3

The second step is to collect the socio-economic effects of drought and heat in urban areas. This means to what extent drought and heat are damaging the infrastructure, economy, ecosystems and wellbeing of residents. This information will be obtained by literature, newspapers and by interviewing waterboards and communities. To gather more information about drought and heat, there will be a fieldwork to New Orleans (27-03-2019/ 08-04-2019). During this fieldwork, I will take interviews from different stakeholders (Annex B). Subsequently, there is a complete collection of information about Dutch and New Orleans drought and heat impacts and causes. All the impacts will be discussed and displayed in tables, photos and drawings. After step two we can analyze the differences and similarities between drought and heat related impacts of the two study areas. As a result, the sub question ''What are the socio-economic impacts of drought and heat, are these impacts different in the Netherlands and in New Orleans and when do these impacts occur?'' will be answered.

Step 4

During the last step, different measures which could be implemented to mitigate the impacts of drought and extreme heat will be analysed. These measures are obtained by consulting different kind of literature (scientific articles and newspapers). At the end future mitigation options and recommendation for future research can be made. This will answer the sub question ''What mitigation options are available to reduce drought impact in the Netherlands and in New Orleans?''

3.2 Background

3.2.1 Climate of the past 1000 years in the Netherlands

In the past 1000 years, cold and warm periods alternate (figure 3.2.1; Buisman & Engelen, 1995). The described years (763-1800) can be roughly divided into three periods (table 3.2). The first period is the Medieval Warm period (1170-1430). This period is characterized by relatively high temperatures compared to the thousand-year average and have its optimum in the middle of the 13th century where the annual temperature was 9°C above the yearly mean of the past thousand years. These temperatures will not be surpassed before the 20th century. After the climate optimum the mean yearly temperature starts to decrease. The second period is the small ice age (1430-1820) which can be subdivided in three main low points and two relatively warmer periods. Since 1430, a serie of severe winters occur, and the number of warm summers decreases. The first warmer period within the small ice age is from 1470-1530. After this period, temperatures are dropping again, and the main low point has been reached 1551-1621. Around 1630, winters are getting normal and around 1650 severe and warm winters alternates. After 1820, temperatures increase steadily. This period is called ''Modern climate optimum''. The colour diagram makes it possible to easily read the different periods and variations (Annex C).

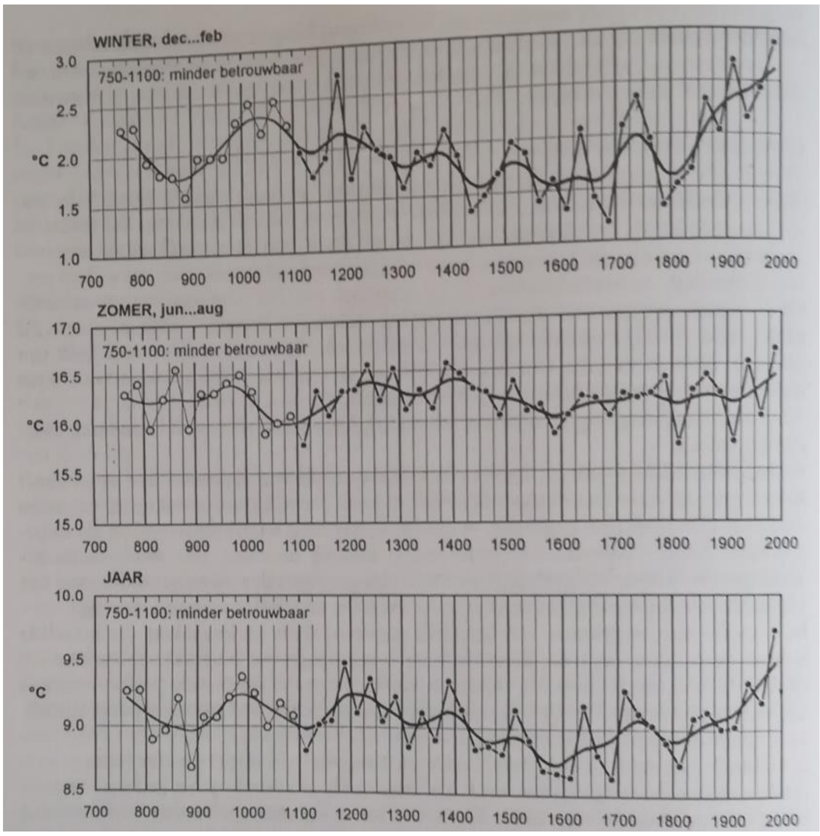


Figure 3.2.1: Averages over 25 years of winter, - summer, spring and autumn temperature and annual temperature in The Lowlands from 700-2000, with 5-point Gaussian filter. Source: (Buisman & Engelen, 1995)

Table 3.2: the different periods with regard to temperature variations from 763 to 1820

Period	Year	Information
Pre Medieval Warm Period	763 -1170	
Medieval Warm Period (1170-1430)	1170-1200 & 1225-1250 1250 1375-1400	Warmest periods of the past thousand years (mean yearly temperatures). Climate Optimum Summers very warm, similar to those in the 2nd half of the 20th century.
Small Ice Age (1430 -1820)	1430-1470 1470-1530 (highpoint) 1551-1621 (Lowpoint) 1690 (Lowpoint) 1700-1750 (highpoint) 1800 (Lowpoint)	The mean yearly temperature drops below the average thousand-year temperatures. Warmer period Colder period (main lowpoint) Colder period (winter temperatures are colder than 1601-1625) Warmer period Colder period
Modern climate optimum	After 1820	Temperatures increases steadily

3.2.2 Climate of the past 1000 years in the USA

Continental-scale temperature variability reconstruction of North- America during the past two millennia are presented in figure 3.2.2. According to Trouet, three low frequency periods can be distinguished. The first is during the Dark ages (500-700 CE) and the Little Ica Age (1200-1900 CE), and the warmer medieval climate anomaly (750-1100 CE). The warmest centuries are the 9th and the 11th and are characterized by centennial-scale aridity in North and West America. Nevertheless, the temperatures of the early 21st century are much warmer.

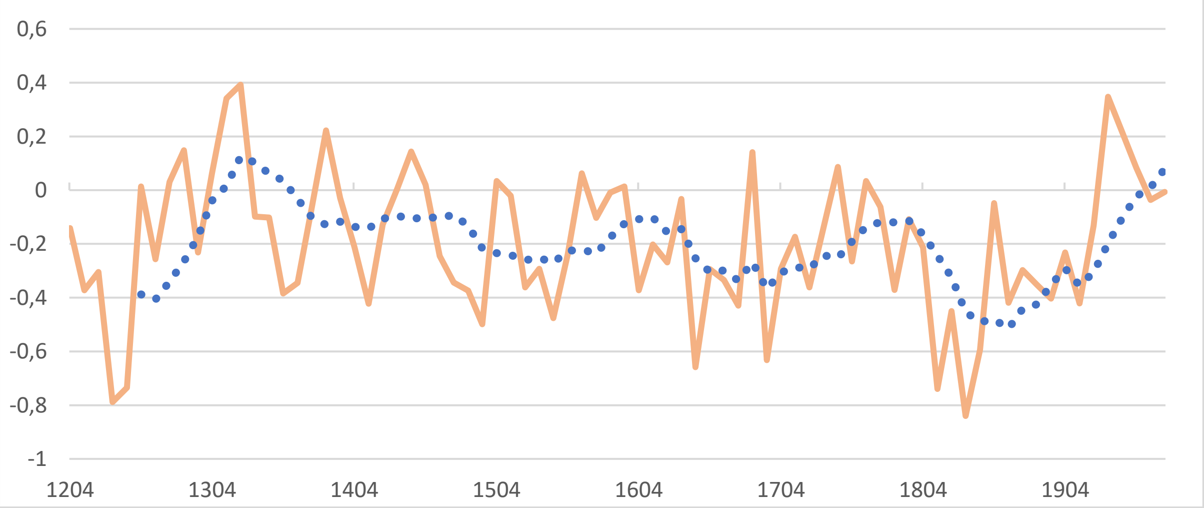


Figure 3.2.2: Annual temperature reconstruction of North America, anomaly with respect to 1904-1980 (°C), using tree rings. Source: (Trouet et al., 2013)

3.2.3 Climate of the past 100 years in the Netherlands

Meteorological data

The current climate in the Netherlands is temperate maritime (climate classification of Köppen). This means relatively mild winters, mild summers and whole year-round precipitation. The Dutch climate is largely influenced by the North Sea. Figure 3.2.3 shows the annual temperature trend of the Netherlands. The mean temperature was 9 °C in 1910 and has increased with 1.9 ±0.6 °C to 10.9 °C in 2015. Currently the average summer temperature has increased with 2,3 ± 0,7 °C in the last 105 years to 17.5 °C (figure 3.2.4).

The annual precipitation has increased too, with 27% over 106 years to 880 mm (figure 3.2.5). Furthermore, the months July to December are the wettest, about 20 mm wetter than the months of January to June (CLO, 2016). In addition, the average evaporation at the west coast is 580-610 mm per year (figure 3.2.6).

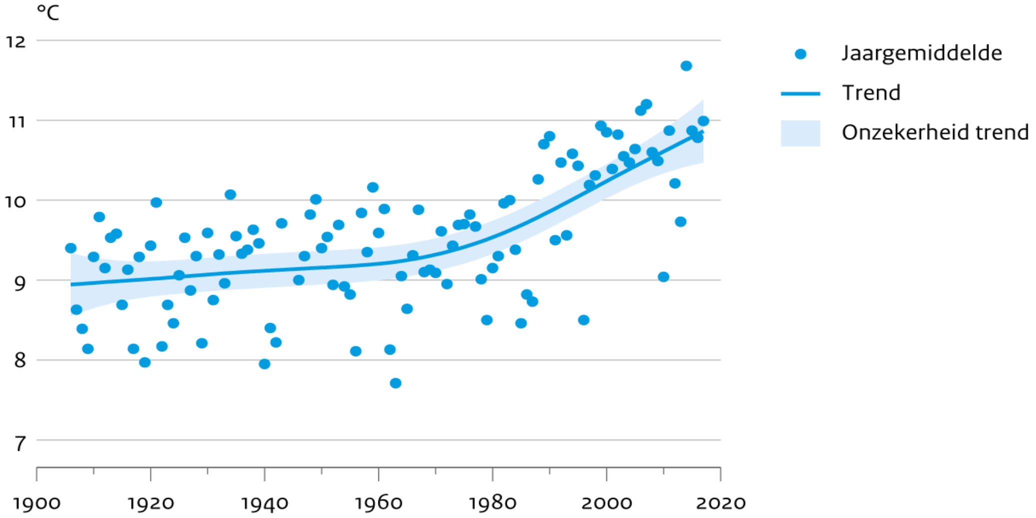


Figure 3.2.3: Annual temperature change in the Netherlands from 1901-2019. Source: (KNMI, 2018e)

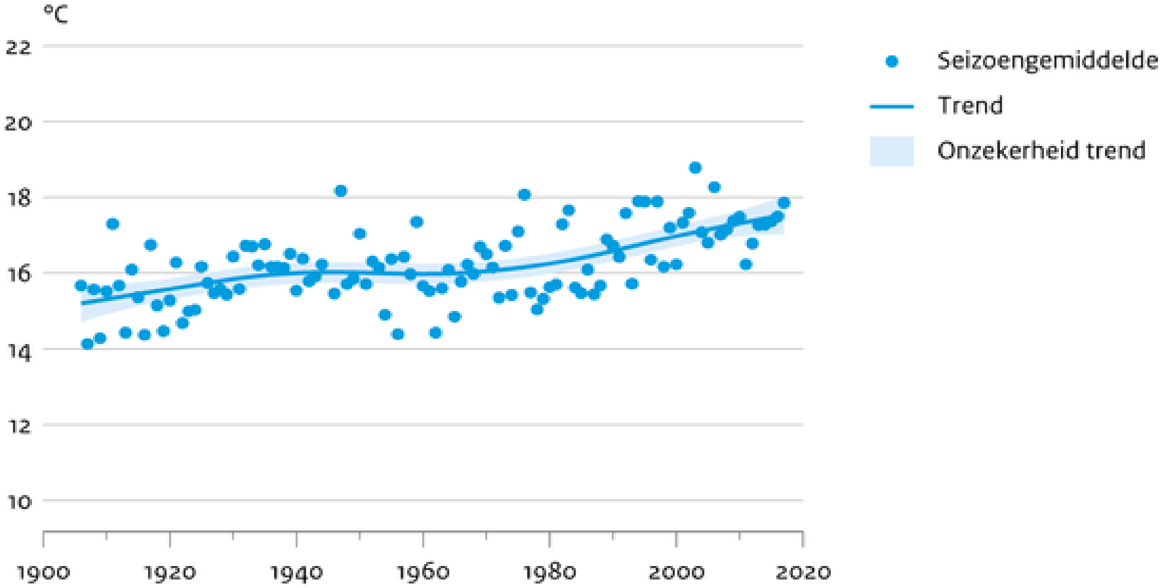


Figure 3.2.4: Temperature change of the Dutch summer from 1901-2019. Source: (KNMI, 2018e)

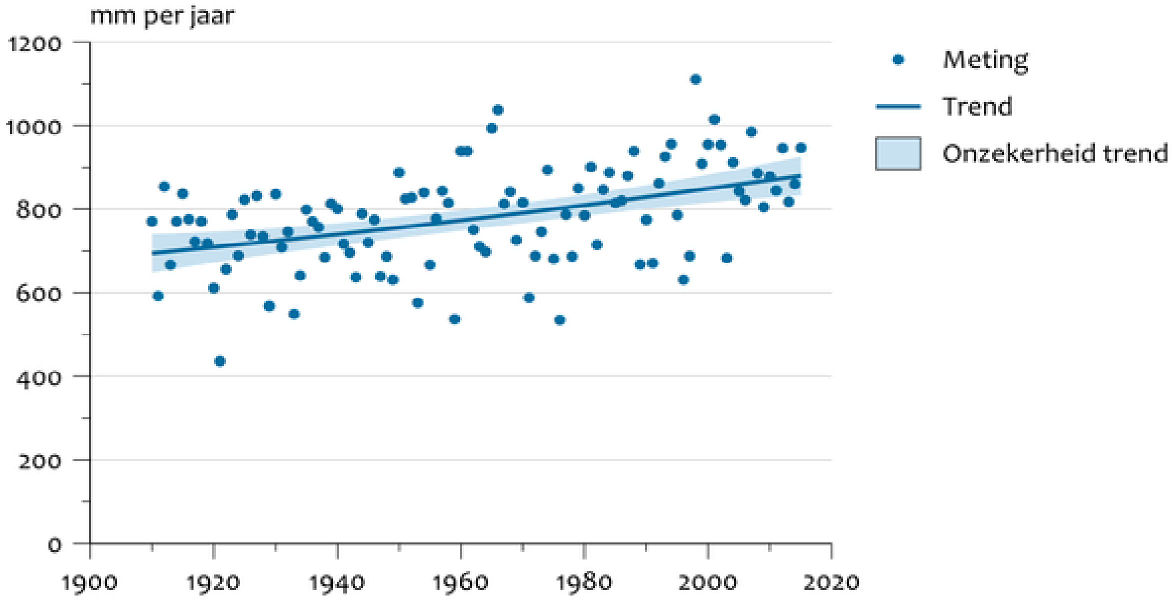


Figure 3.2.5: Annual precipitation change of the Netherlands from 19010-2019. Source: (KNMI, 2018e)

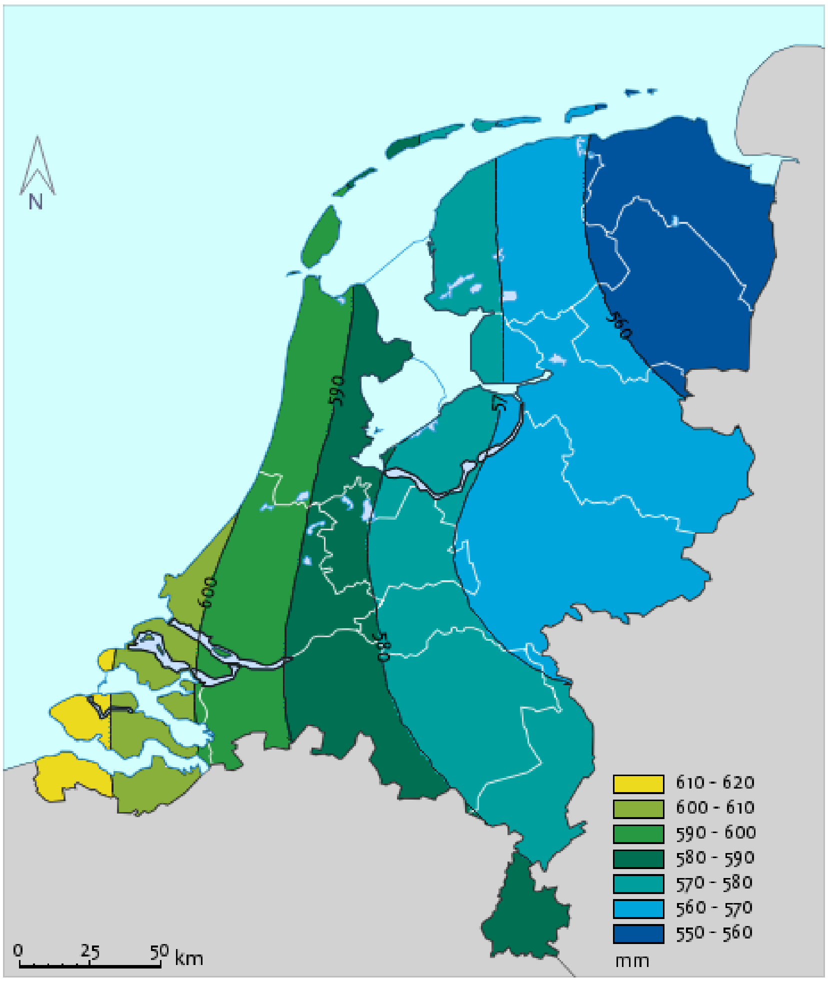


Figure 3.2.6: Long term average yearly evaporation (1981-2010). Source: (Klimaatatlas, 2018)

Droughts

Figure 3.2.7 shows the precipitation deficit of 1976, 2003 and 2018. The maximum deficit is in general at the end of August or at the start of September. The precipitation deficit of the driest year (1976) was 361 millimetres instead of an average summer which has a deficit of around 100 millimetres. In 2003, the precipitation deficit was 228 millimetres. This was enough to cause serious drought related damages. Furthermore, last summer was an extreme dry year with a precipitation deficit of 296 millimetres. Figure 3.2.8 shows the PDSI values to indicate drought in the Netherlands, the lowest peaks are 1921, 1960, 1976, 1979, 1990 and 2003 (PDSI ≤ -3 is severe drought).

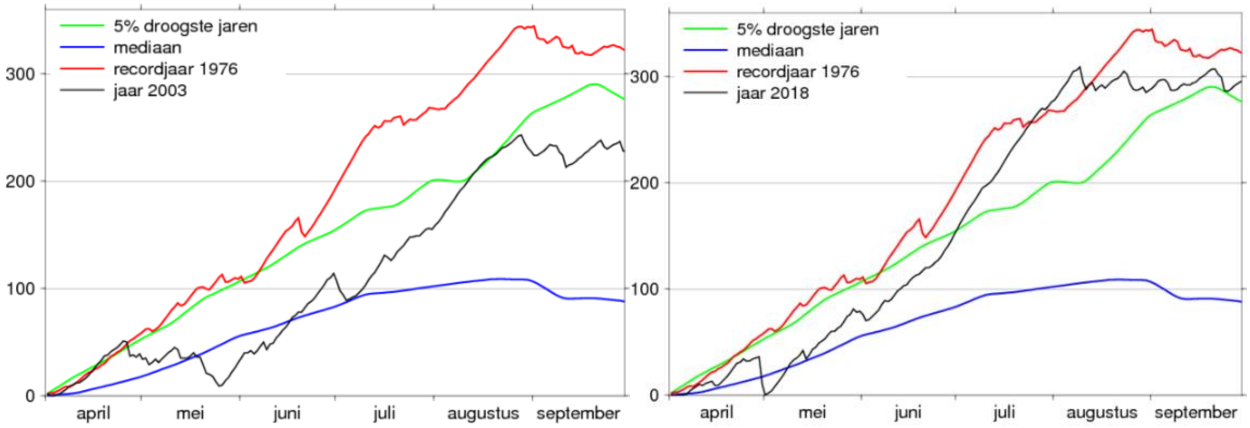


Figure 3.2.7: Precipitation deficit in the Netherlands in 2003 (left); Precipitation deficit in the Netherlands in 2018 (right). The y-axis shows the precipitation deficit in millimetres. Green= 5% driest years, blue= median, red= record year 1976 and black = 2003. Source: (KNMI, 2018c)

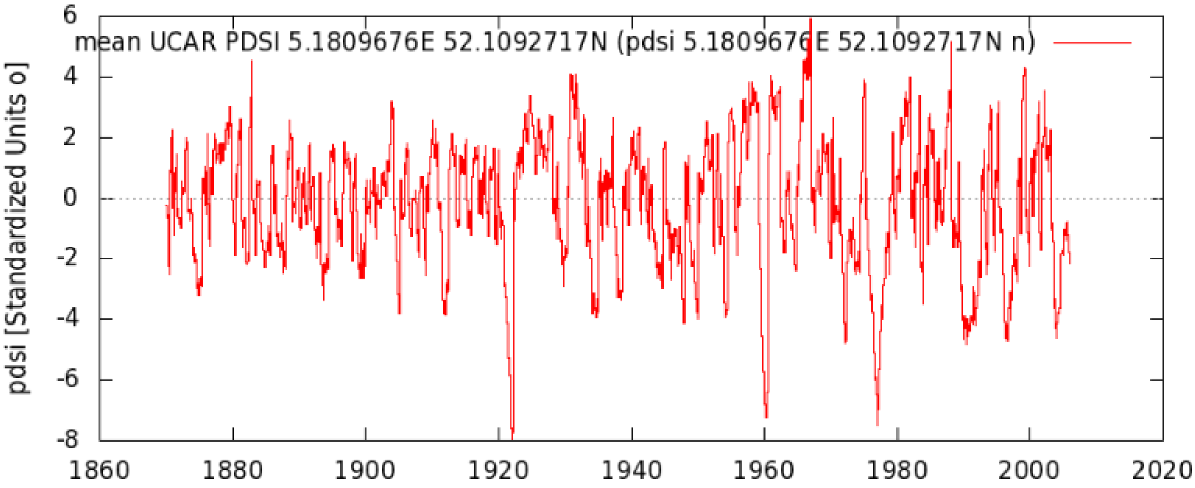


Figure 3.2.8: Monthly UCAR PDSI, coordinates 5.1809676E 52.1092717N (De Bilt; 1870-2005). Operating on Global Monthly Dai Palmer Drought Severity Index, taking grid box region longitude= 5.000 7.500, latidue= 50.000 52.500, pdsi [Standardized Units o]. Source: (Climate explorer, 2018a)

Rhine river

The Rhine originate in the Swiss Alps and enters the North Sea in the Netherlands (table 3.3; figure 3.2.9). The river is a meltwater and precipitation fed river with a discharge varying between 600-16000 m3/s (Lobith, border Germany/The Netherlands). Furthermore, the river provides the Netherlands with fresh water and is an important shipping route. Therefore, insufficient discharges in the river leads to high economic impacts. When the discharge is below 1100 m3/s at Lobith (figure 3.2.10), the freshwater supply of the western Netherlands may be at risk, resulting in salinization of the Rijnmond area. At that moment the Small-scale Water Supply (KWA) enter into force and supplies freshwater from the Amsterdam Rijnkanaal and the Lek to West- Holland (Hoogheemraadschap van Rijnland, 2019).

Table 3.3: general Rhine information

Source	Lake Toma, Switzerland
Elevation	2,340 m
End	North Sea (Rotterdam)
Length	1320 km
Watershed	185,000 km2
Average Discharge	2200 m3/s
River flow	0,5 - 1,5 m/s (The Netherlands)

Figure 3.2.9: Catchment area of the Rhine river. Source: (Water diplomacy, 2014)

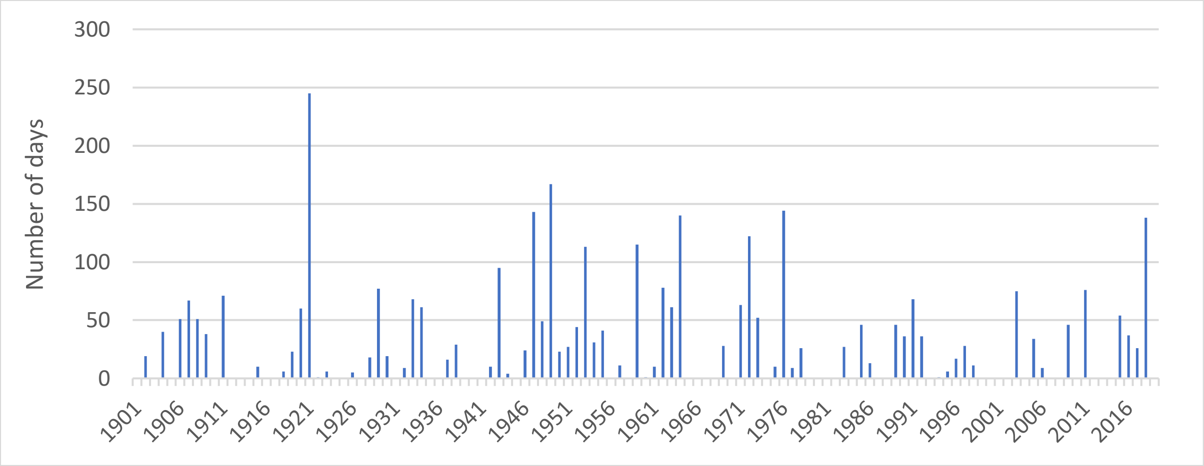


Figure 3.2.10: Number of days that the discharges of the Rhine becomes below 1100 m3/s

3.2.4 Climate of the past 100 years in New Orleans

Meteorological data

New Orleans, Louisiana is located at the Gulf of Mexico and has a subtropical climate. The climate characterises with hot, humid summers, tempered by frequent afternoon thunder showers and relatively mild winters. In New Orleans, the average annual temperature has increased with 2.4 °F to 21.3 °C (70.4 °F) in 2015 (figure 3.3.1). In addition, the region is affected by the hurricane season which extends from June to November.

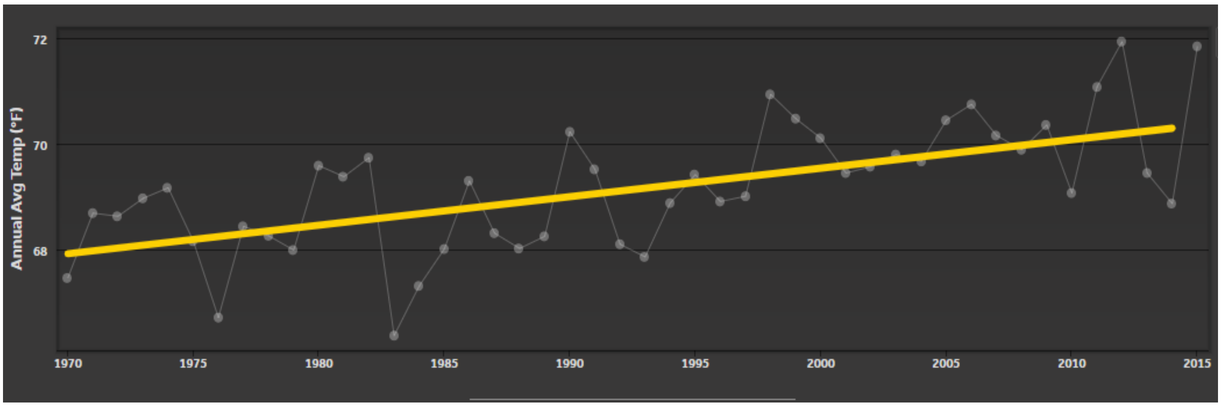


Figure 3.3.1: Annual average temperatures in New Orleans from 1970-2015. Source: (wxshift, 2016)

Furthermore, New Orleans is the 15th hottest city in the U.S (Climate Central, 2016a). The monthly temperatures are showed in figure 3.3.2 and annex D. From June to September, the highest average temperatures are rising above 30°C (86 °F). In these months the lowest temperatures are not getting below 21°C (69,8°F). July is the warmest month, the average day time temperature increases to 32,8 °C (91,1°F). The coldest month is January with an average temperature overnight of 6,3°C (43,4°F).

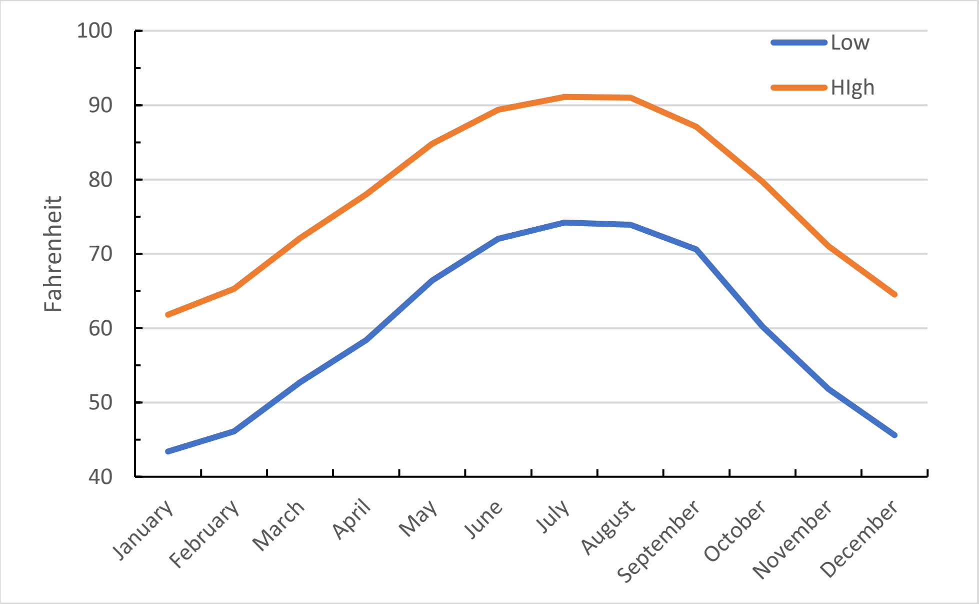


Figure 3.3.2: Average temperatures New Orleans. Source: (rssWeahter, 2015)

Currently, temperatures above 35°C (95°F) are occurring on average less than 10 times a year (Figure 3.3.3). The year with the highest number of days exceeding 35°C was 1980 (38 days). However, models show an increase in extreme warm days up to 50 days per year in 2050 and at the end of this century it could go up to 130 times per year. In addition, there is an upward trend of the dewpoint temperature from 1980-2015 (Annex E). This is increased by 2,5°F from 72 to 74,5 °F and implies that summers are getting muggier.

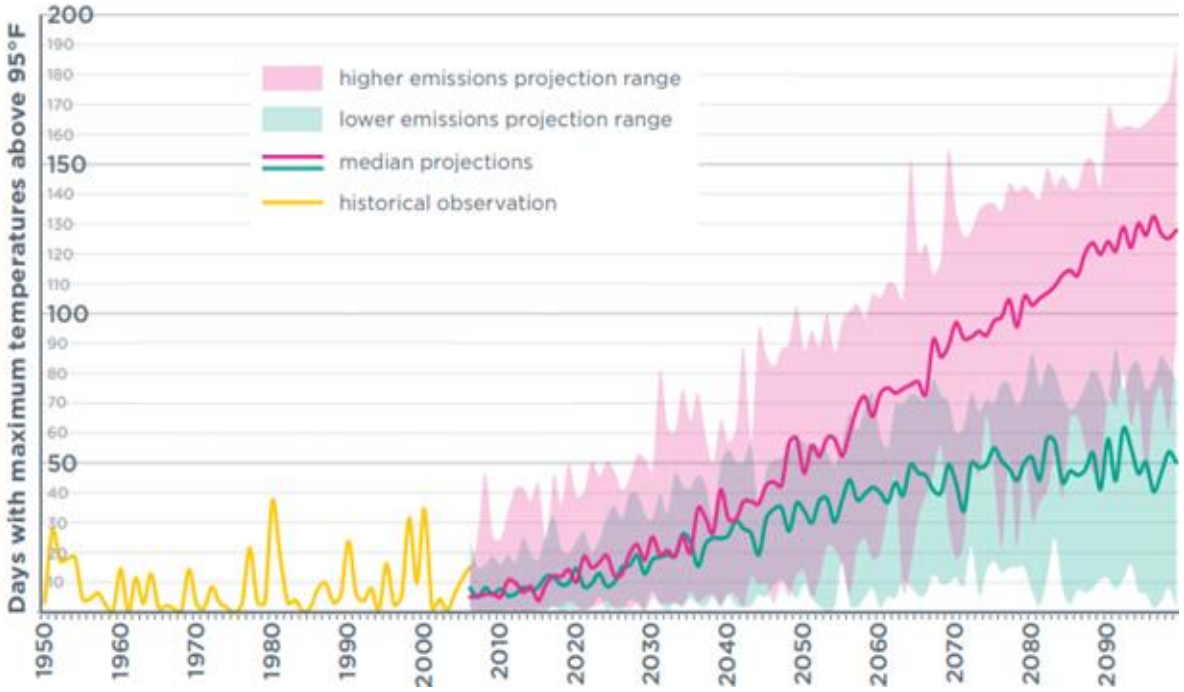


Figure 3.3.3: The number of days New Orleans experiences temperatures above 95°F (Source: NOLA, 2017)

New Orleans has whole year-round rainfall. The annual precipitation trend shows a small decline (figure 3.3.4). In 1970, it was 1620 millimetres (63,7 inches) and in 2015, it was 1593 millimetres (62,7 inches). However, during the period 1970-2015, the summers became wetter from 452 to 505 millimetres (17,8 to 19,9 inches; Figure 3.3.5). Figure 3.3.6 and annex F shows the monthly precipitation amounts. October is the driest month with 76 millimetres (3 inches) of precipitation. June is with 174 millimetres (6.9 inches) the wettest month.

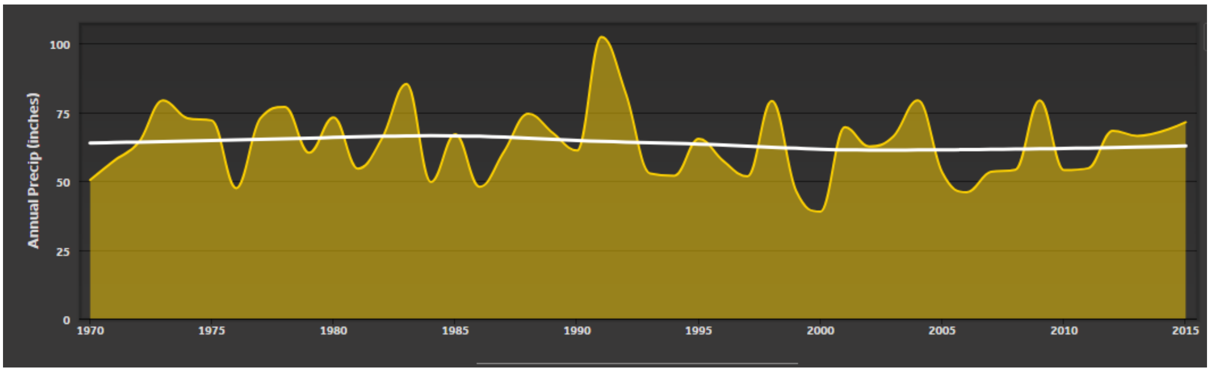


Figure 3.3.4: Annual precipitation trend of New Orleans from 1970-2015. Source: (wxshift 2016)

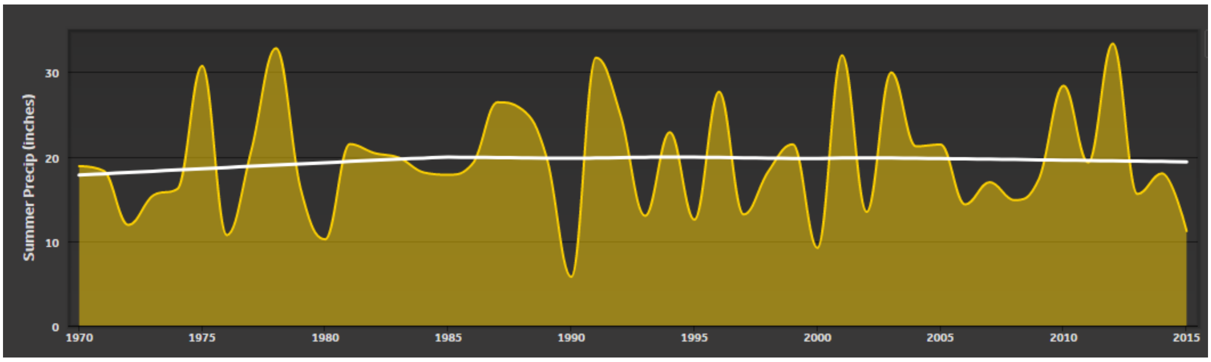


Figure 3.3.5: New Orleans summer precipitation trend from 1970 to 2015. Source: (wxshift, 2016)

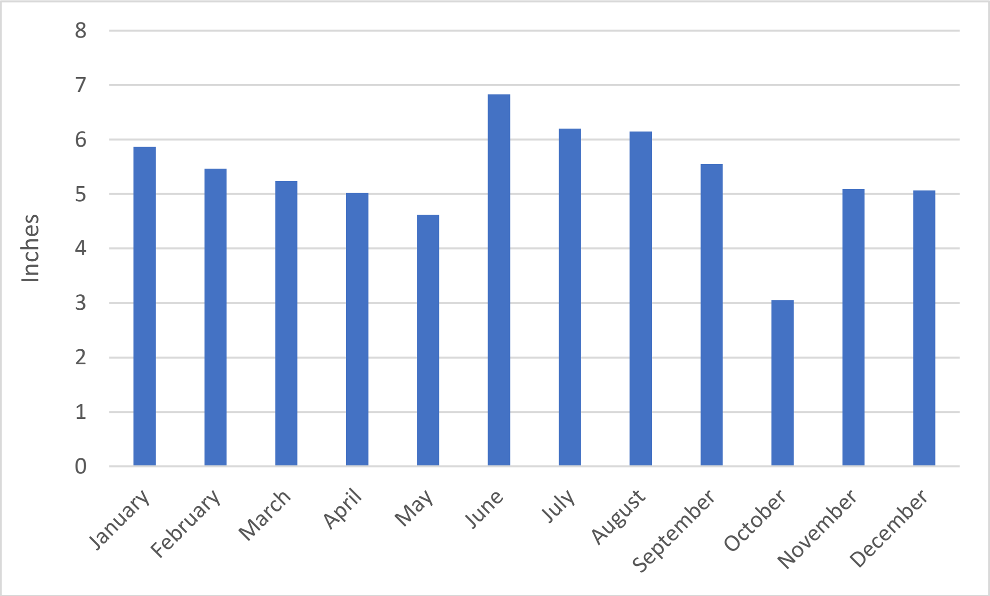


Figure 3.3.6: Average Rainfall in New Orleans per month. Source: (rssWeahter, 2015)

Drought

The U.S. experienced several severe drought events in the past century. The most extreme drought occurred in 1930s with a peak in July 1934 (the dust bowl years). During this period, 60% of the country suffered from extreme drought conditions, there were large economic damages and millions of people migrate from the plains to other parts (NOAA, 2019). According to NOAA, 26 drought events occurred in the period from 1980-2018. The most severe drought appeared in 1988, 2000, 2002, 2006 and 2012-2013. These events caused losses exceeding $1 billion each across the United States. As a result, large agricultural losses, water rationing, and large number of wild fires appeared across the country. Nevertheless, severe drought (PDSI ≤ -3), appeared less than 5% of the time between 1895–1995 in Louisiana (Figure 3.3.7). However, in the last 20 years, drought appeared in 2000, 2006 and 2011 (figure 3.3.8). The driest year was 1963 (Willis, 2011). Therefore, these four years are analysed for in New Orleans (Chapter 4.4).

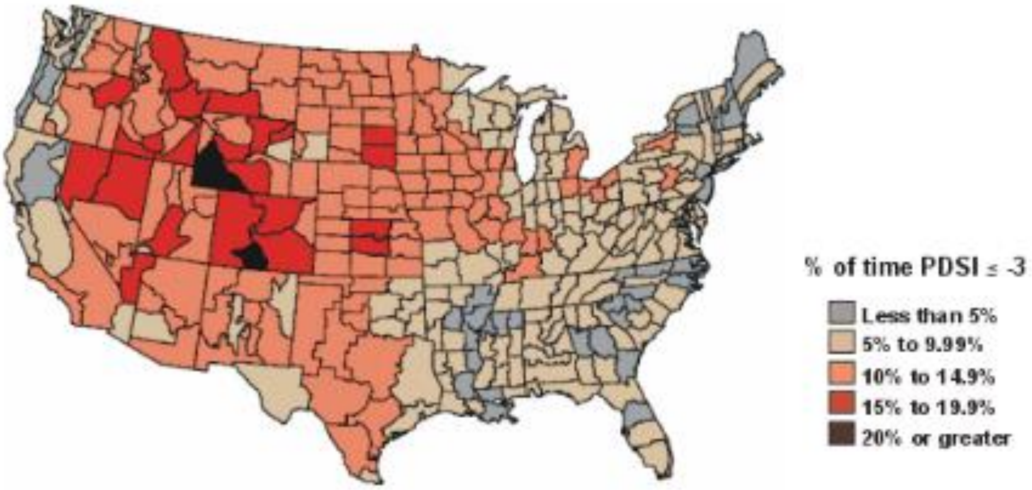


Figure 3.3.7: Palmer drought severity index (1895-1995), percent of time in severe and extreme drought. Source: (NDMC, 2019)

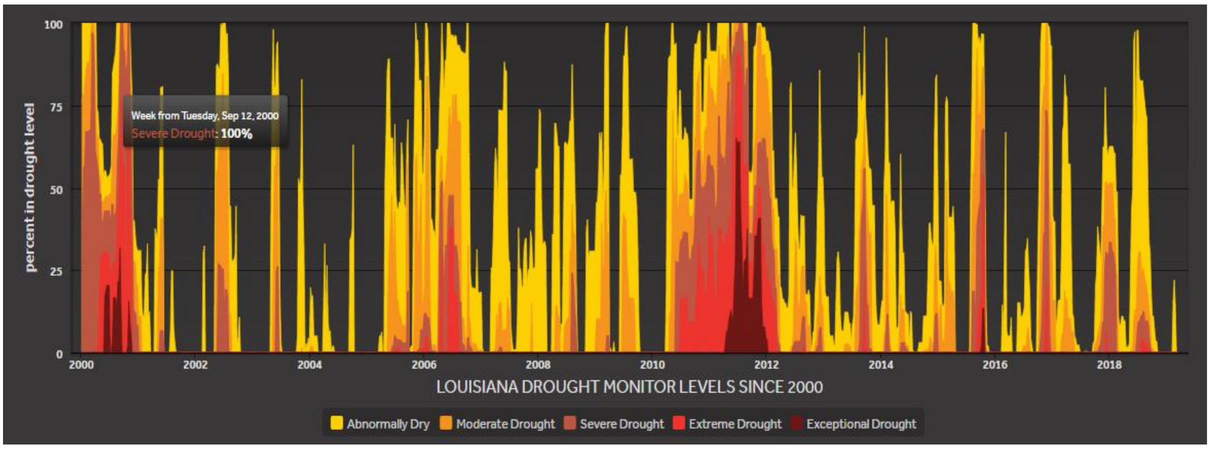


Figure 3.3.8: Louisiana drought monitor levels since 2000. Source: (Wxshift, 2019)

Mississippi river

The Mississippi is the second largest river in North America and the 15th largest river in the world. The catchment area of the river covers almost 40% of the US territory including 32 US states and two Canadian provinces (Figure 3.3.9). Table 3.4 shows more characteristics of the Mississippi river. The Mississippi is similar to the Rhine an economical main port and the water is used for the production of public drink water. The Low Water Reference Plane has been introduced in 2014 to determine when the river discharges becoming too low (Hunter et al., 2014). This reference plane is a hydraulic-based, statistical vertical datum for channel depths. It is designed for the Orleans District whereby the Mississippi from mile 313.7 to 265.4 is based on a 97% discharge duration of 4134 m3/s (146,000 cfs) at Tarbert Landing (1954-2005). How often the Mississippi discharge was below this plane is showed in figure 3.3.10.

Table 3.4: Mississippi general information. Source: (National Park Service, 2018)

Source	Lake Itasca, Minnesota
Elevation	1,475 ft (450 m)
End	Golf of Mexico (New Orleans, Louisiana)
Length	3782 km
Watershed	3.2 million km2
Average Discharge	593,003 cubic feet/ second (16792 m3/s)
Average speed	19.3 km/uur
Main water source	Rainfall

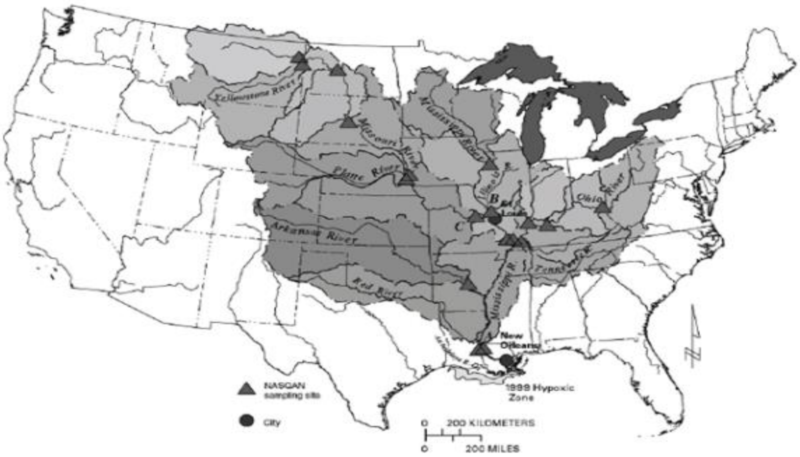


Figure 3.3.9: Watershed Mississippi. Source: (Goolsby & Battaglin, 2001)

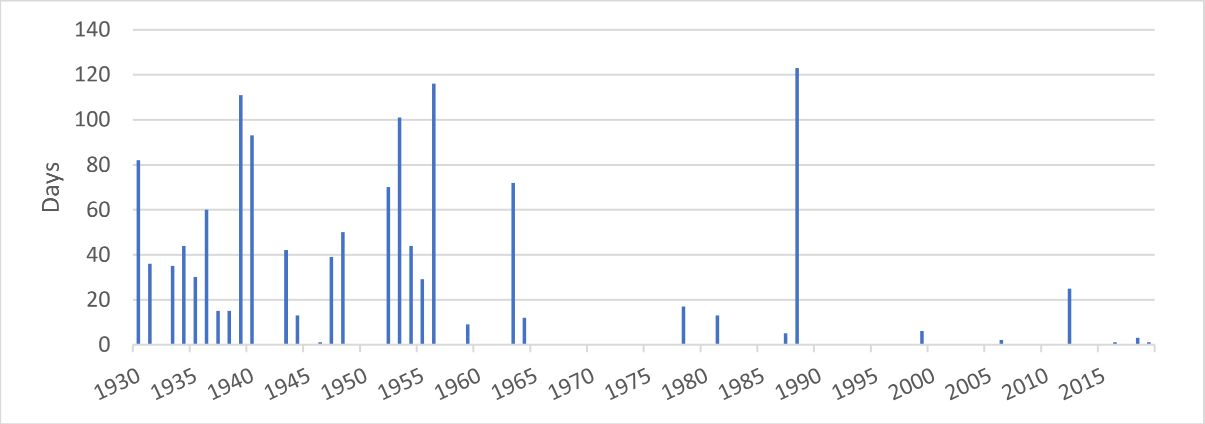


Figure 3.3.10: Number of days that Mississippi discharges are below The Low Water Reference Plane (4134 m3/s) in the period 1930-2019.

3.2.5 Future climate change

According to the KNMI Climate Explorer, the mean annual temperature will increase between 2 and 3 °C due to climate change in New Orleans (Louisiana) and in the Netherlands at the end of this century (Figure 3.4.1).

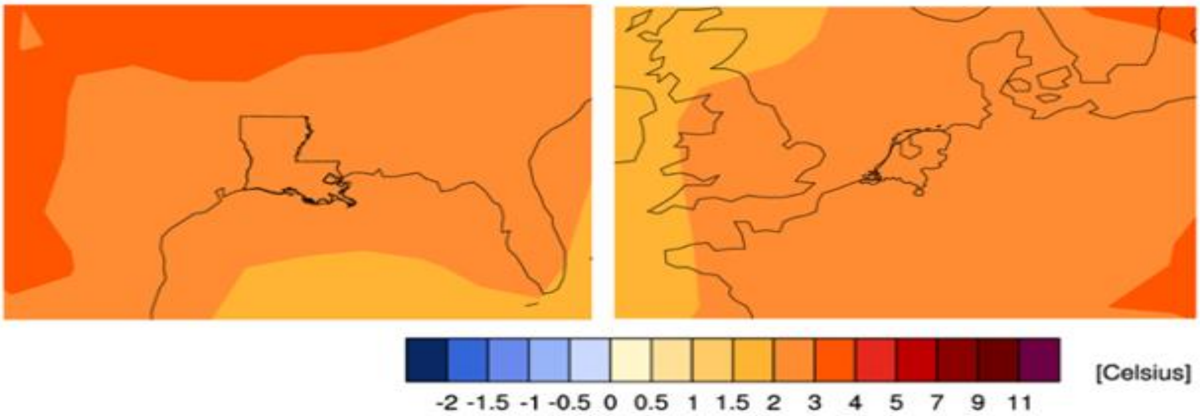


Figure 3.4.1: The mean annual temperature changes 2081-2100 compared to 1986-2005 (Jan-Dec Ar5 CMIP5 subset). Based on rcp 6.0 scenario. Left: Louisiana, right: the Netherlands. Source: (KNMI, 2019)

Due to the expected higher temperatures, evapotranspiration will increase too (EPA, 2017). Figure 3.4.2 shows the evapotranspiration change at the end of this century. In New Orleans there will be an increase between 0.1 and 0.5 mm/day. The evaporation increase in the Netherlands will be between 0.1 and 0.2 mm/day (KNMI, 2019).

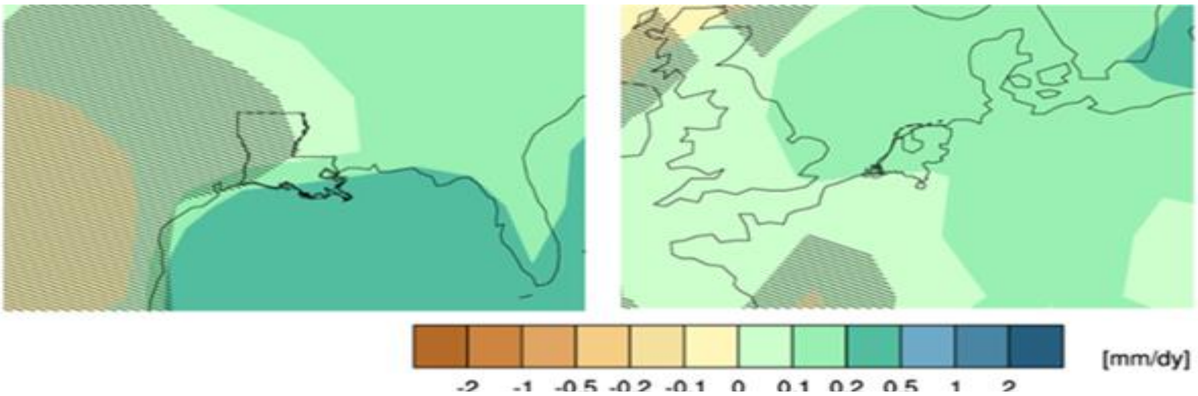


Figure 3.4.2: The mean annual evapotranspiration changes 2081-2100 compared to 1986-2005 (Jan-Dec Ar5 CMIP5 subset). Based on rcp 6.0 scenario. Left: Louisiana, right: the Netherlands. Source: (KNMI, 2019)

According to figure 3.4.3, the period between April to August becomes wetter in New Orleans (0.1-0.2 mm/day) and the Netherlands become slightly dryer (0-0.1 mm/ year). Furthermore, precipitation events presumably become more intense under a warmer climate (Ye et al., 2016). This could cause more drought because more rainwater will fall in a shorter amount of time, and consequently be lost to surface runoff and not contribute to the groundwater via soil infiltration (Figure 3.4.4).

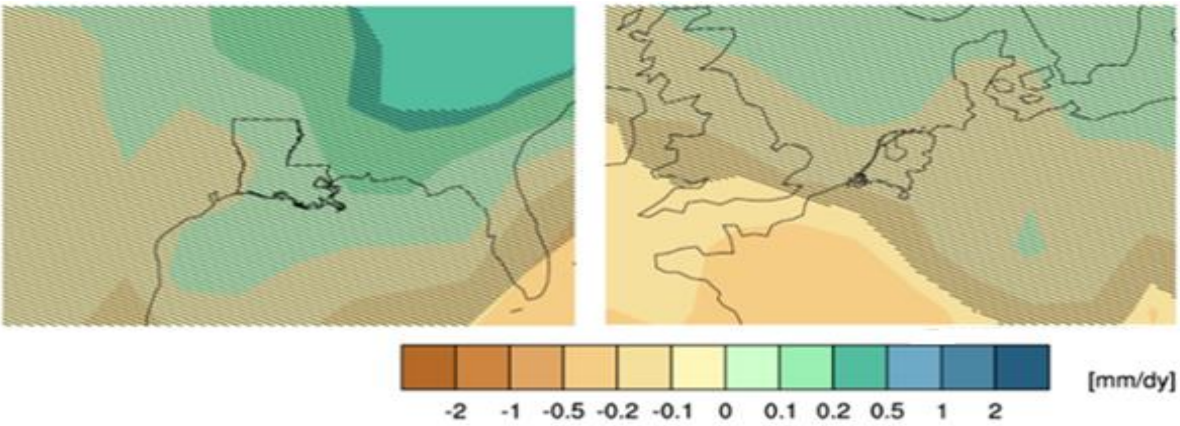


Figure 3.4.3: Mean precipitation changes from April to August in 2081-2100 compared to 1986-2005 (April-August); The hatching represents areas where the signal is smaller than one standard deviation of natural variability). Based on rcp 6.0 scenario. Left: Louisiana, right: the Netherlands. Source: (KNMI, 2019)

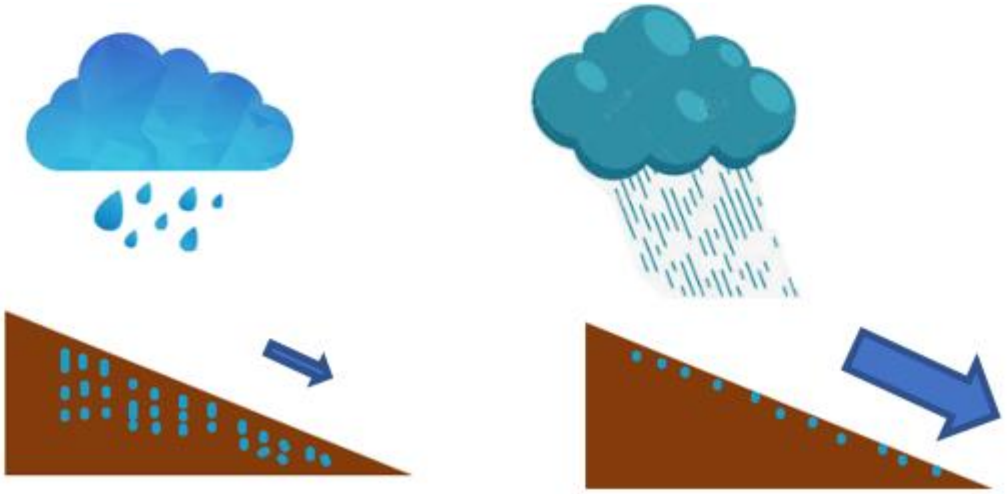


Figure 3.4.4: Low rainfall intensity results in large soil infiltration and small runoff (left); high rainfall intensity results in high runoff and less infiltration.

4. Results

4.1 Drought and heat events of the past 1000 years

Figure 4.1.1 shows severe drought events, plus the correlating heat intensity between 1300 to 1800 (AD). During the Small ice age (1430-1820), drought events occurred often without extensive heat. However, when mean summer temperatures are high, drought and heat are often compound events. One remarkable event was the great solar year in 1540. This year was warmer and drier then the drought in 2003 (wetter et al., 2014). The impacts of drought and heat are described and visualized (figure 4.1.2) below. The full description of all drought and heat related impacts are presented in Annex G.

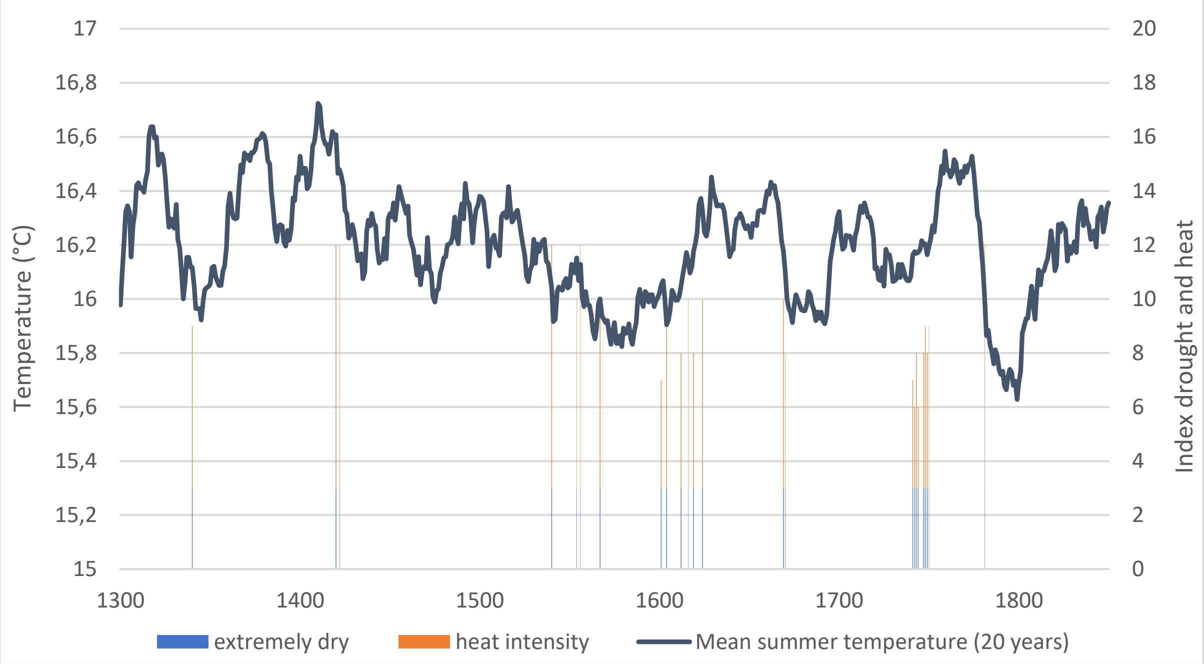


Figure 4.1.1: The average summer temperature in time in combination with the occurrence of extremely dry periods and the corresponding heat intensity during 1300-1800

Insects & vermin

Warm and dry periods accompany with insects & vermin plagues which among others damaged the harvest (mice, flies, fleas, locusts & caterpillars). One possible explanation is the lack of food and water during these periods.

Famine

Famines are not always related to drought and heat. They occurred also due to severe winters, dry spring or cold and wet summers (1313-1314-1315-1316-1317). Besides, local weather events as hail and thunder storms were able to destroy the harvest too. However, these thunderstorms are often a result of warm weather precedes. After the 16th century, there was more export which declines the risk to famines.

Air pollution

The first-time air pollution was described in 1173 which was caused by nearby peat and forest fires and urbanisation. During hot and dry summers (1185 and 1288), cities almost became unliveable due to bad smells and smog caused by the small businesses including butchers, tanners, glass blowers, slaughterhouses and the open sewers.

Illness

The black plague often returned. Remarkable is that the disease killed one third of the population of Gallia and Germany during the warm and dry summer of 874 and 994. However, the disease appeared often during colder periods and less at extreme warm and dry conditions. This because the fleas that transmit the illness have optimal living conditions at 20 °C with high humidity. One disease which is related to high temperatures during summer are the smallpox. In 1422, reports described that many children and adults got the smallpox due to extreme heat. Especially children became seriously ill and either died or remained blind. Moreover, many people working on the fields died due to heat stress.

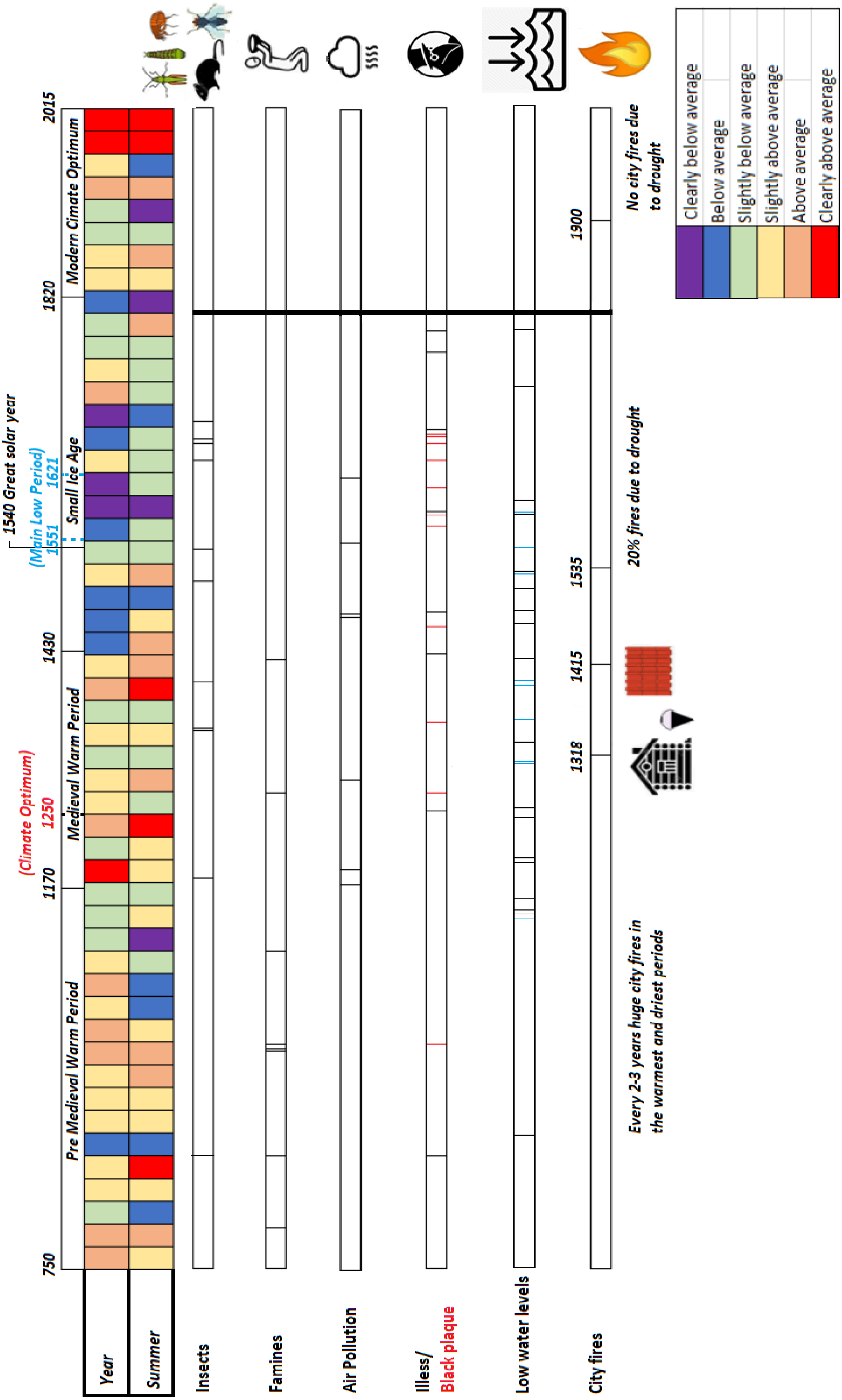
Low river levels

Descriptions of low river levels started around the Medieval Warm Period. Additional descriptions of low water were dried out wells, small streams, swamps, water sources, ditches, canals and ponds. Several times farmers had to walk with their cattle many miles searching for water. Moreover, due to a lack of water, the rate of fish mortality was high, grasslands and trees started to wither, and water became more expensive than wine (1517).

City fires

In the Pre- Medieval Warm Period, all houses were made from tarred wooden walls and reed/straw roofs which quickly caught fire. The use of candles, open fires and storage of slightly combustible materials were common and therefore cities were very vulnerable for fires, especially during drought periods when there was little fire-extinguishing water, a city could completely put into ashes within hours. During the warmest and driest decades of the 13th and 14th century, every 2-3 years people were startled by huge city fires. During the 15-16th century, there was a gradual decline of fires due to the use of brick walls and roof tiles in the big cities and the people were recommended to lubricate houses with sludge and to check their chimneys (1424). Since 1530-1540, large fires were decreasing and around 1667-1750, no major fires occurred in the larger cities anymore. However, small villages burned down due to the factor drought until the 19th century. Dry periods, heat waves, a lightning strike, carelessness and wartime were the many causes of city fires.

Figure 4.1.2: Important drought impacts from 750-1800 (AD)



4.2 Drought and heat in the Netherlands (past 100 years)

4.2.1 Precipitation deficit

Table 4.2.1 present the driest years according to the precipitation deficit plus corresponding heatwave days and PDSI values. The meteorological characteristics are further analyzed for the driest year on record 1976 and the two recent drought periods 2003 and 2018.

Table 4.2.1: The maximum precipitation deficit + occurrence of heatwaves of the top 10 most drought years since 1906, averaged over the Netherlands.

Rank	Year	Precipitation deficit (mm)	Return time (Year)	**Heatwave days**	**Mean PDSI April-September**
1	**1976**	**361**	**90**	**17**	**-4,9**
2	**1959**	**352**	**70**	**-**	**-2,6**
3	**1911**	**328**	**70**	**7**	**-2**
4	**1921**	**321**	**45**	**-**	**-4,8**
5	**2018**	**309**	**40**	**23**	**?**
6	**1947**	**296**	**25**	**8**	**-1,9**
….					
10	**2003**	**234**	**10**	**14**	**-2,03**

4.2.2 PDSI monthly

The PDSI values per month during the time period 1901-2005 are presented in figure 4.2.1. The PDSI values show a correlation with the extreme dry years according to the KNMI (1921, 1959, 1976 and 2003). The lowest values are reached in the winter of 1921/1922 with PDSI values of almost -8. The lowest PDSI value of 1976 was -7 in December. All PDSI values of the driest years are showed in Annex H. Only 1921 and 1976 were dry for an entire year.

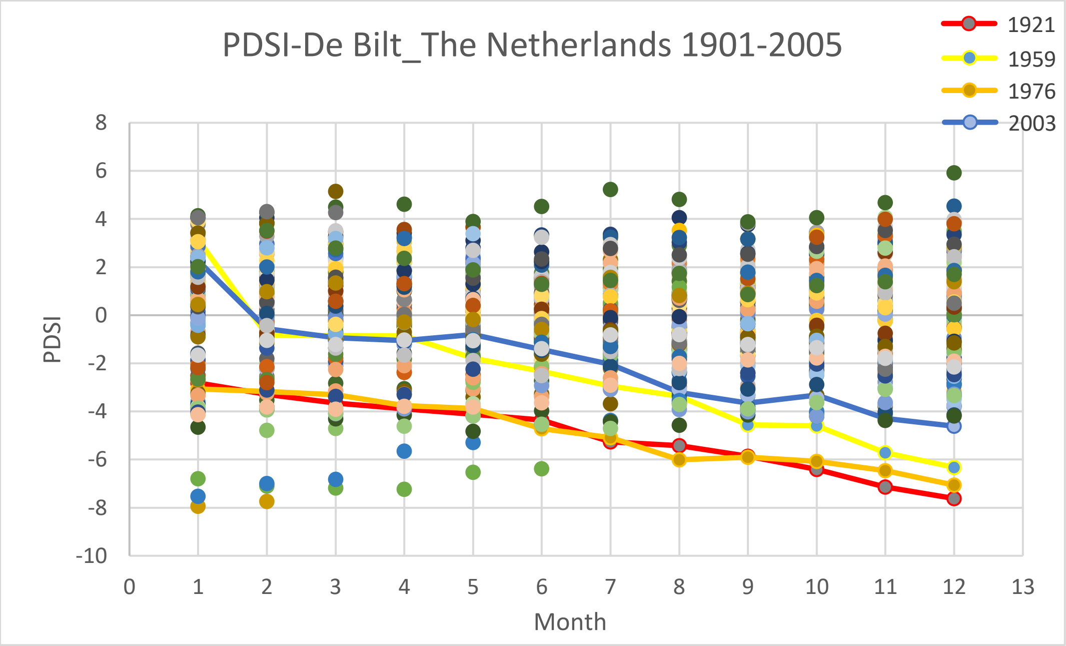


Figure 4.2.1: PDSI values per month (1901-2005)

4.2.3 Temperatures and Precipitation

The sum of monthly precipitation varies widely between the dry years (Figure 4.2.2; table 4.2.2). The period from 1 April to 30 November of 1976 and 2018 belongs to the 5% driest years since 1906. The driest year (1976), had extreme low precipitation rates in April, May and August compared to an average year. Moreover, from May to August temperatures are higher than normal. In 2003, temperatures were above normal from May to September. Precipitation rates are almost all lower than average, especially July and August were extremely dry (<50% compared to average). Notable is the rainfall in May which was higher than normal. Extremely dry periods in 2018 are June and July with 50% less precipitation than normal (11,8 & 5,3 millimetres). The temperatures from April to August, were above normal. Moreover, the temperature in April was already 4 °C higher than in 1976 and 2003. In general, the temperatures of the three dry years were higher than average and precipitation values are below normal.

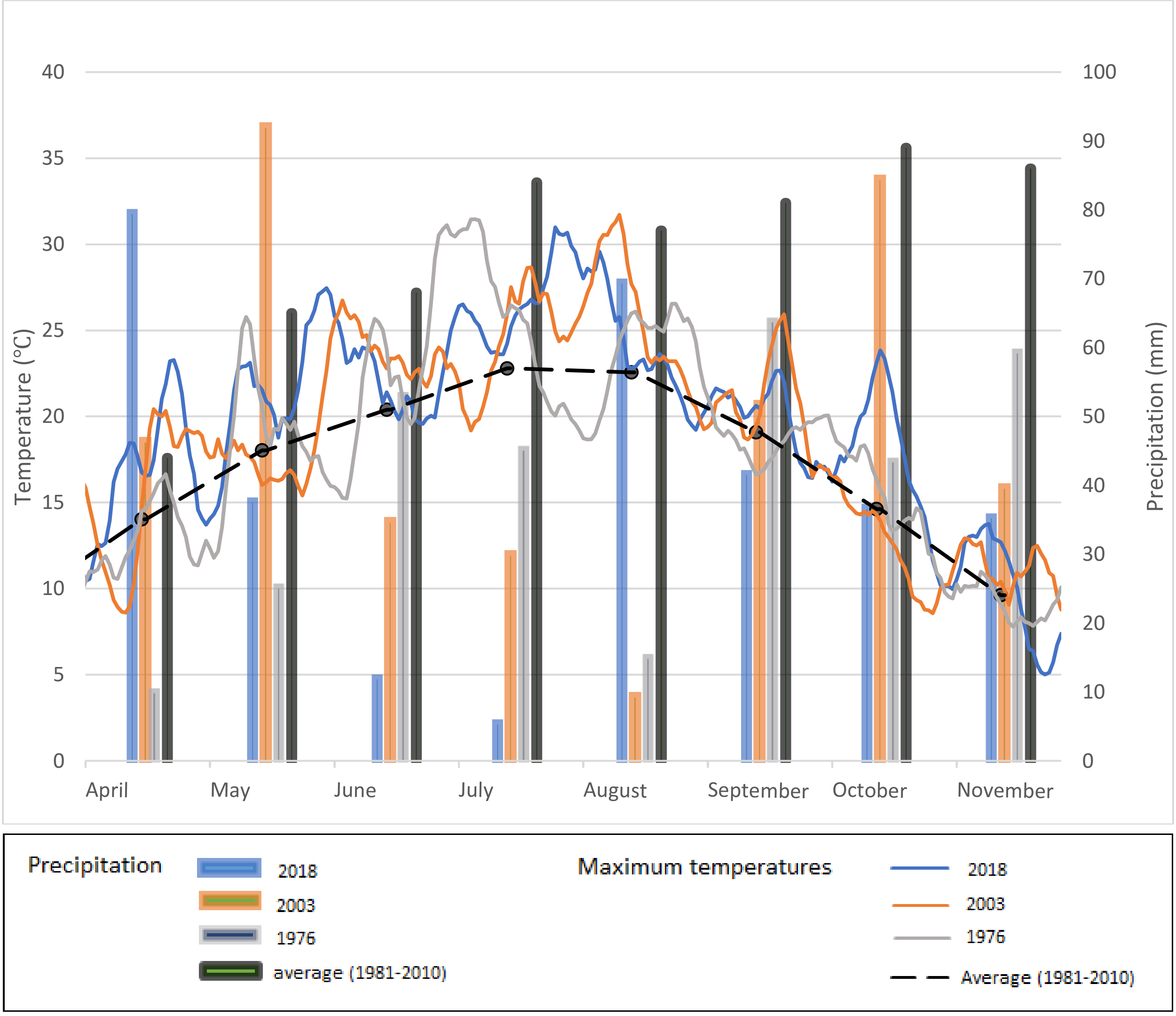


Figure 4.2.2: Temperature and precipitation of the most recent drought years compared with the driest year

Table 4.2.2 Sum precipitation (mm), Normal = the long-term average over the period 1981-2010 (De Bilt)

	1976	**2003**	**2018**	**Normal**
April	9,8	46,2	79,4	44
May	25	91,9	37,5	65
June	52,8	34,6	11,8	68
July	45	29,8	5,3	84
August	14,8	9,2	69,3	77
September	63,6	51,6	41,5	81
October	43,3	84,3	36,6	89
November	59,1	39,5	35,2	86
total	313,4	387,1	316,6	594

4.2.4 Heatwaves

Due to rising temperatures of the past century, the number of heatwaves has increased just as the duration (Figure 4.2.3). In the first 50 years, there were 7 heatwaves (1901-1950). The second half of the 20th century consisted 9 heatwaves and since 2000 there already appeared 10 heatwaves (KNMI, 2018d). In addition, except for 1921 and 1959, every drought year was compounded with a heatwave. Most heatwaves appear in July and August. Furthermore, the longest during heatwave occurred in 1975 with respectively 18 consecutive days and the highest temperature within a heatwave was measured in 2006 and 2018 (35,7°C). All heatwaves which are measured in the Bilt since 1901 are showed in annex I.

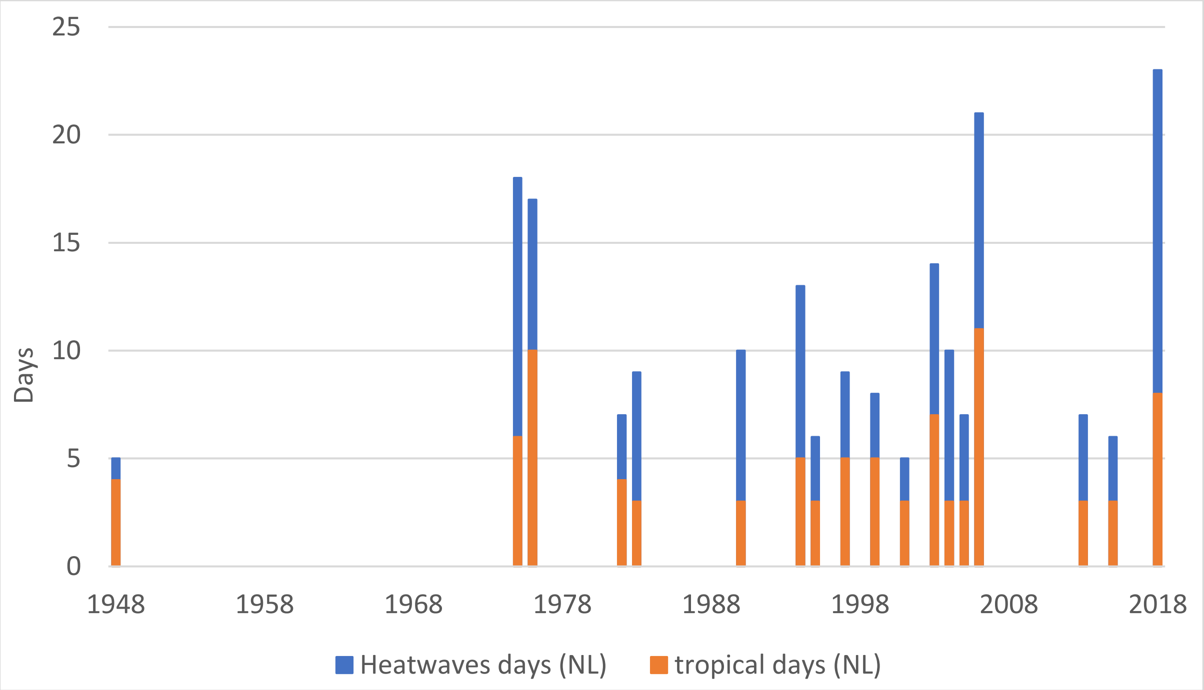


Figure 4.2.3: Cumulated number of heatwave days within a year (All days cumulated that satisfy 5 consecutive days or more above 25 °C of which at least 3 are above 30°C) and the cumulated tropical days (30°C or more) which has appeared within a heatwave in the Netherlands.

4.3 Drought in combination with discharge Rhine

The lowest discharges are reached during the end of summer. This because in the summer it is often dryer, evaporation rates are higher and all the ice and snow from the Alps are melted. In the drought years, the discharges are getting below the 1100 m3/s. In the driest year 1976 this occurred in July and September. In 2003, discharges were for a long time below this line from August until October and in 2018 the longest continuous period below the 1100 m3/s appeared from August to December (Lowest point 740 m3/s in November). However, the lowest discharge ever measured since 1900 is 620 m3/s in November 1947 (Waterpeilen, 2018a).

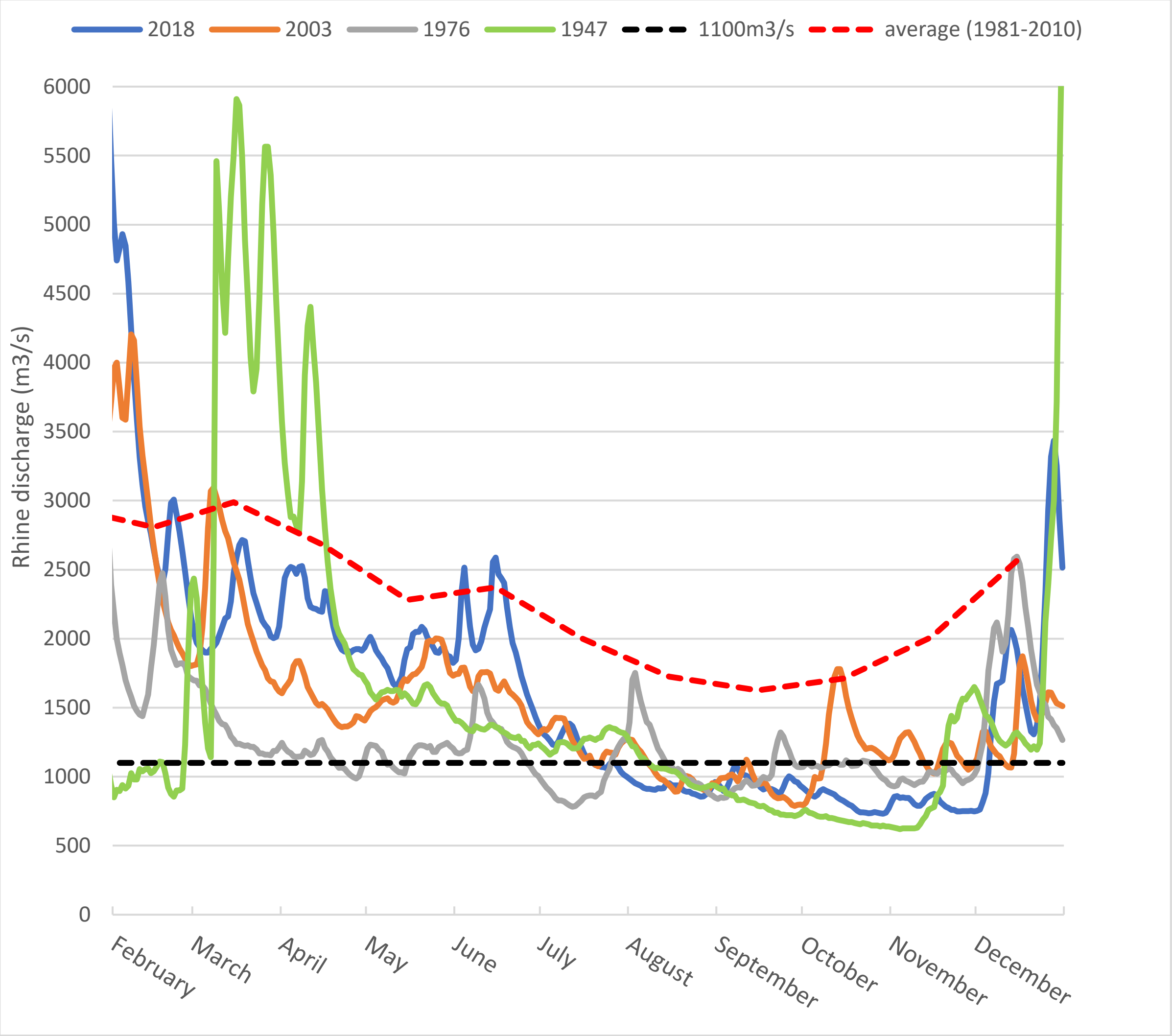


Figure 4.3.1: Rhine discharges of the drought years 1947, 1976, 2003 and 2018 plus 1100 m3/s line from February until December.

According to Deltares, there is a relationship between high precipitation deficits in the Netherlands and low Rhine discharges (figure 4.3.2). This correlation is also visible using monthly PDSI values and the discharge deficits during the months April to July (figure 4.3.3) and August to October (Annex J). From April to July, the discharge deficit varies between 0 and 1900 m3/s and from August-November it varies between 0 and 1300 m3/s. The variation is smaller because at the end of the summer the discharges are always lower and approaches the baseflow of the river. In both figures, negative PDSI values (≤ -2) correlates with a higher precipitation deficit. Notable, the SPEI values of the Netherlands does not show a clear correlation with low discharges (figure 4.3.4; Annex K). This difference occurred because the PDSI values are only suitable for monitoring mid- and long-term droughts while SPEI can monitors short term drought (Zhao et al., 2017). So, short-term drought correlated less with low discharges.

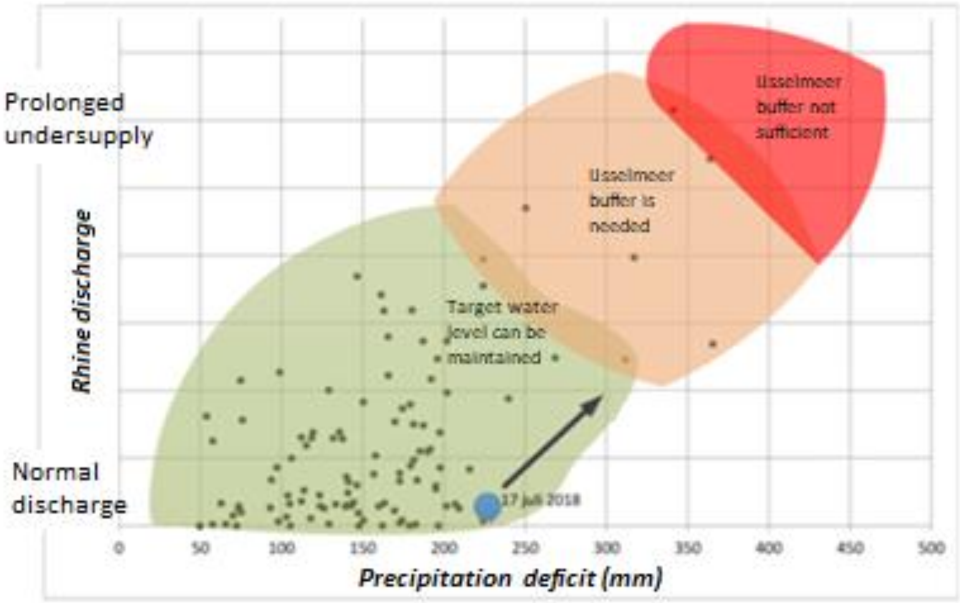


Figure 4.3.2: Precipitation deficit in relation with the discharge of the river Rhine from different years. Source: Deltares, 2018a.

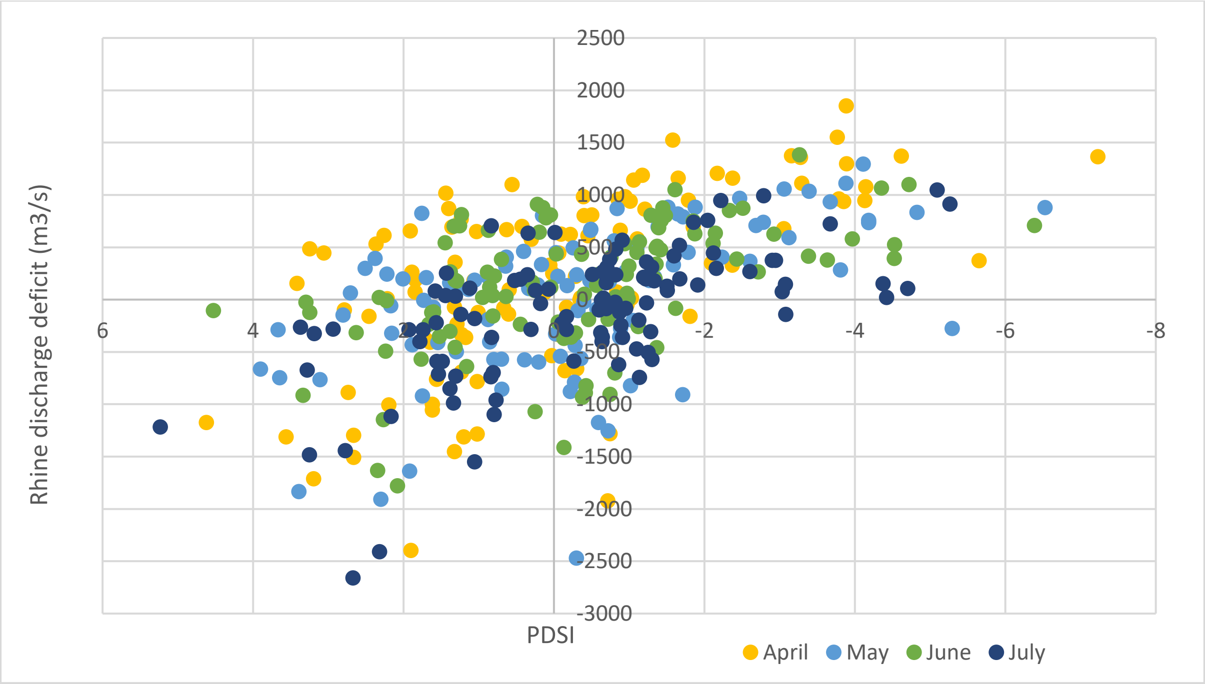


Figure 4.3.3: Mean discharge and PDSI number of April to July (1901-2005). The discharge is expressed as discharge deficit compared to the long-term monthly average discharge.

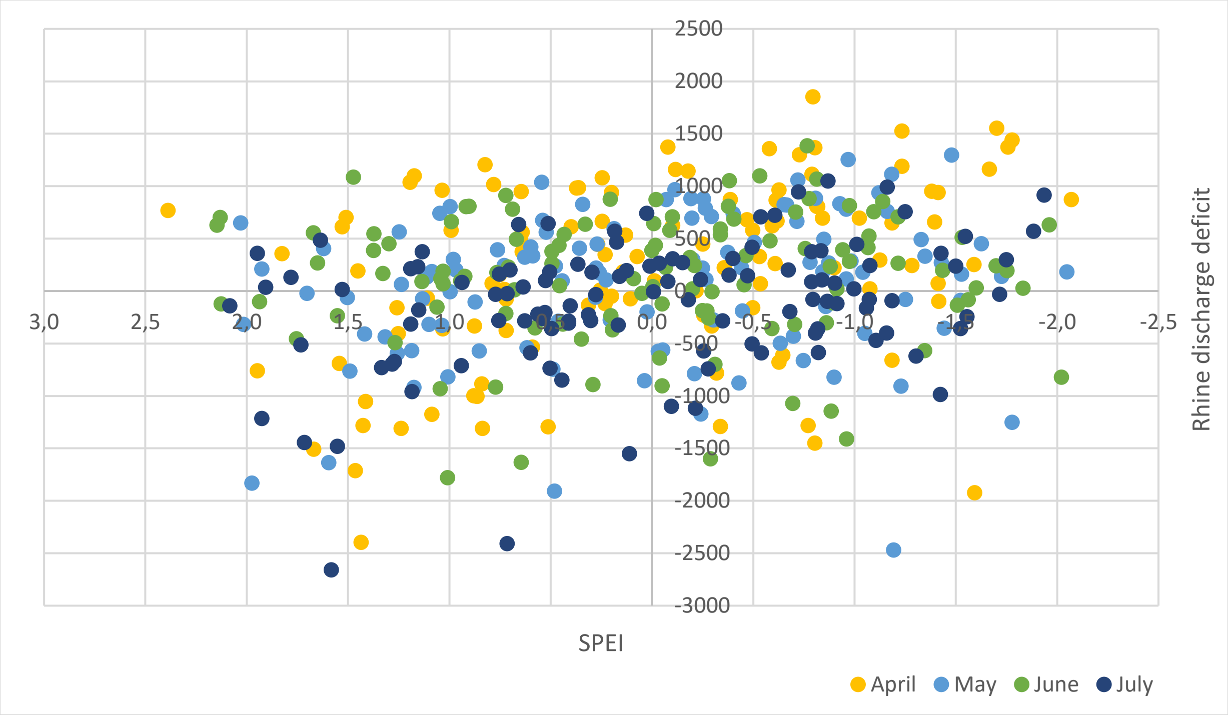


Figure 4.3.4: Mean discharge and SPEI number from April to May (1901-2005). The discharge is expressed as discharge deficit compared to the long-term monthly average discharge.

4.4 Drought and heat in New Orleans (past 100 years)

4.4.1 PDSI

The available PDSI values for the county Orleans are showed in figure 4.4.1 and Annex L (1975-2010). In 1975, the PDSI value was just below 1. In 2010, it was around the -1 which indicating an increasing trend in more dry periods. There is a large variation in PDSI values during a year and within a month. The lowest PDSI values were in 2000 and 2006 with respectively -6,16 (August) and -4,6 (July). Interesting is that the top 5 driest periods all appeared after 1999 (table 4.4.1).

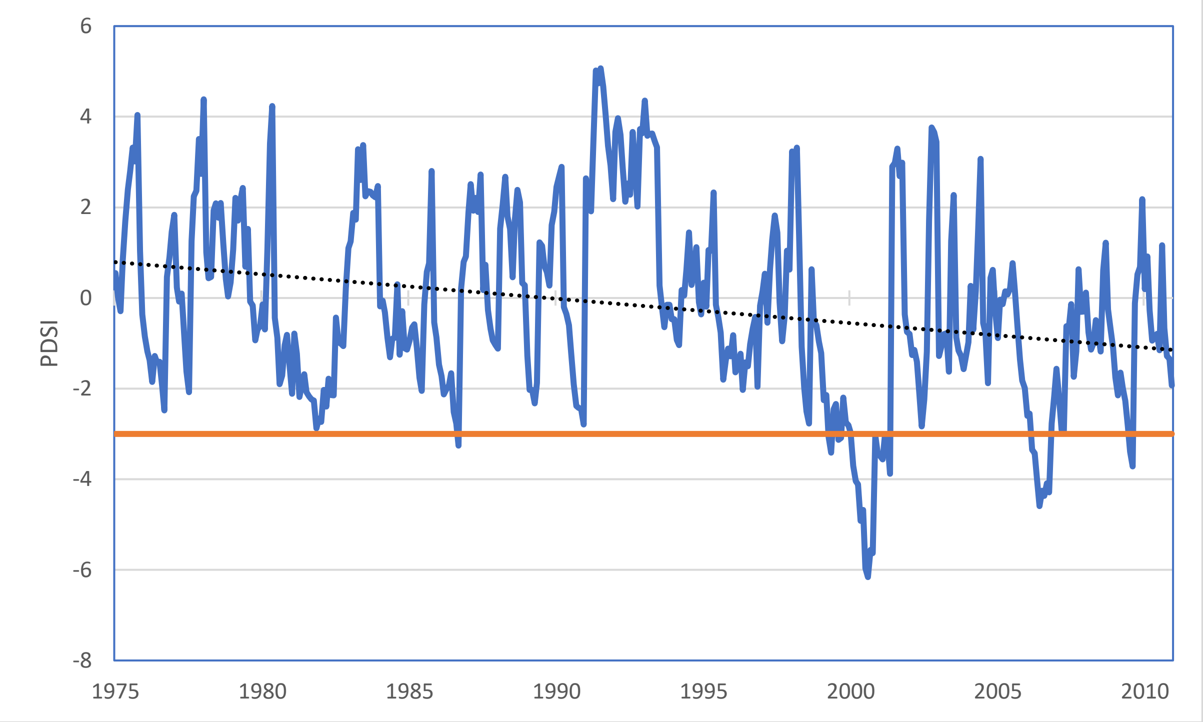


Figure 4.4.1 Monthly PDSI severity index on county level (Orleans) in time period 1975-2010. The area below the orange line represents severe drought (PDSI ≤ 3).

Table 4.4.1 Top 5 PDSI Orleans (1975-2010)

Rank	Year	Month	PDSI
1	**2000**	**August**	**-6,16**
2	**2006**	**July**	**-4,6**
3	**2001**	**May**	**-3,88**
4	**2009**	**August**	**-3,72**
5	**1999**	**May**	**-3,42**

4.4.2 Precipitation deficit

The precipitation deficits are calculated using the Dutch method. The top 5 driest years related to the highest precipitation deficit are displayed in table 4.4.2. The highest values often appear at the end of September (end of measurement period). The highest deficits appeared in 1976 and 1990 with a value respectively of 636 & 615 millimeters (Figure 4.4.2). The driest years expressed in precipitation deficit do correlated with the years with the lowest pdsi values in the same period. Therefore, it is expected that precipitation deficits are even higher in 2000 and 2011. However, 1963 should be the driest period according to literature but does not have the highest precipitation deficit (470 millimeters).

Table 4.4.2 Top 5 Precipitation deficit New Orleans (1961-1990).

Rank	Year	Precipitation deficit (mm)	Date
1	**1976**	**636**	**September 30**
2	**1990**	**615**	**September 30**
3	**1972**	**571**	**September 29**
4	**1967**	**528**	**September 28**
5	**1985**	**534**	**Augustus 08**

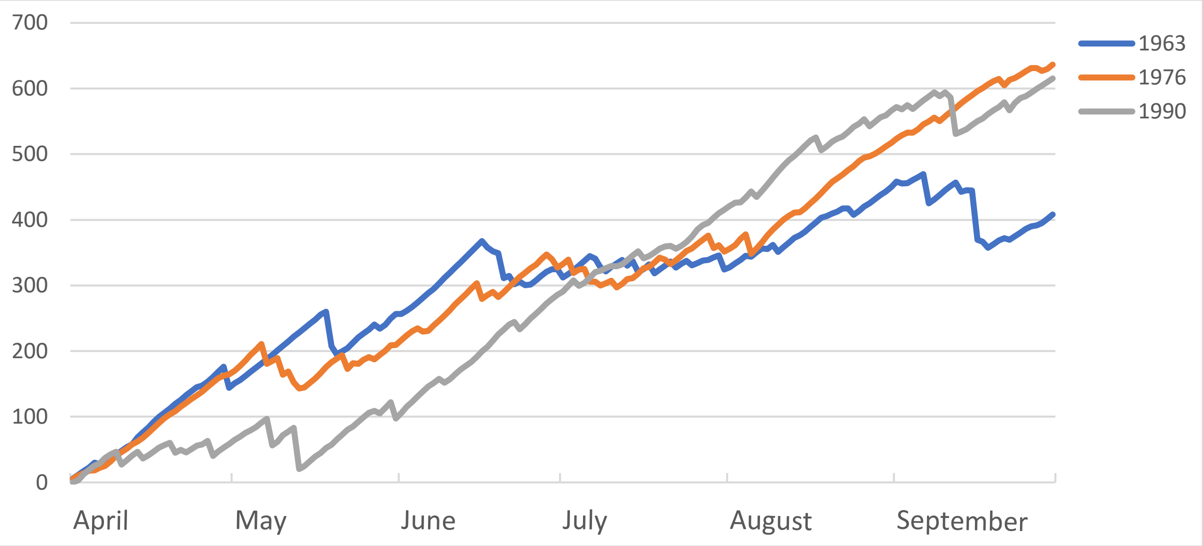


Figure 4.4.2 Precipitation deficit New Orleans New Orleans (1961-1990).

4.4.2 Temperatures and Precipitation

Figure 4.4.3 shows the precipitation and temperatures of 1963 and 2000 compared to the long-time average and 2000 and 2011 are displayed in figure 4.4.4. Besides all values are listed in Annex M. During an average year, there falls 1650 millimeters of precipitation. In 1963, it was 1277 millimeters. Significantly dry months were March, April, August and October. Temperatures were 3 °C higher than average in March and April. However, the other months were almost as high as average. In the first half of 2000, the temperature was higher than normal. In addition, there was significant less rainfall from January to May and in July and August. As a result, there fell only 988 millimeters during the year. In 2006, the meteorological characteristics are the same as 2000. In the first half year, temperatures were higher and there is less precipitation from January until June. After June the temperature is like the long-term average just as the precipitation values. In 2011, temperatures are from February to August higher than normal. Moreover, the months February, April, May, August and October are significant dryer. However, precipitation values in March, July and September are almost double as high as normal.

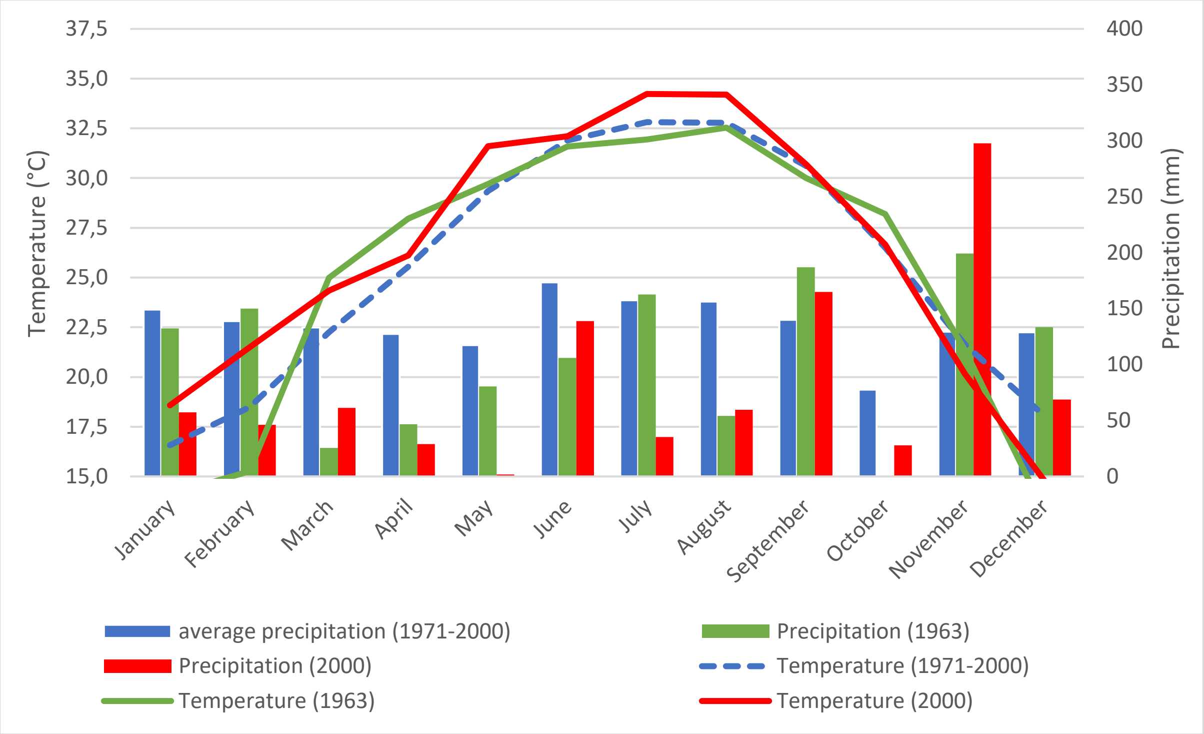


Figure 4.4.3: The average daily maximum temperatures per month and the monthly precipitation of in New Orleans during the drought years 1963 and 2000, compared with the average temperature and precipitation data of the period 1971-2000.

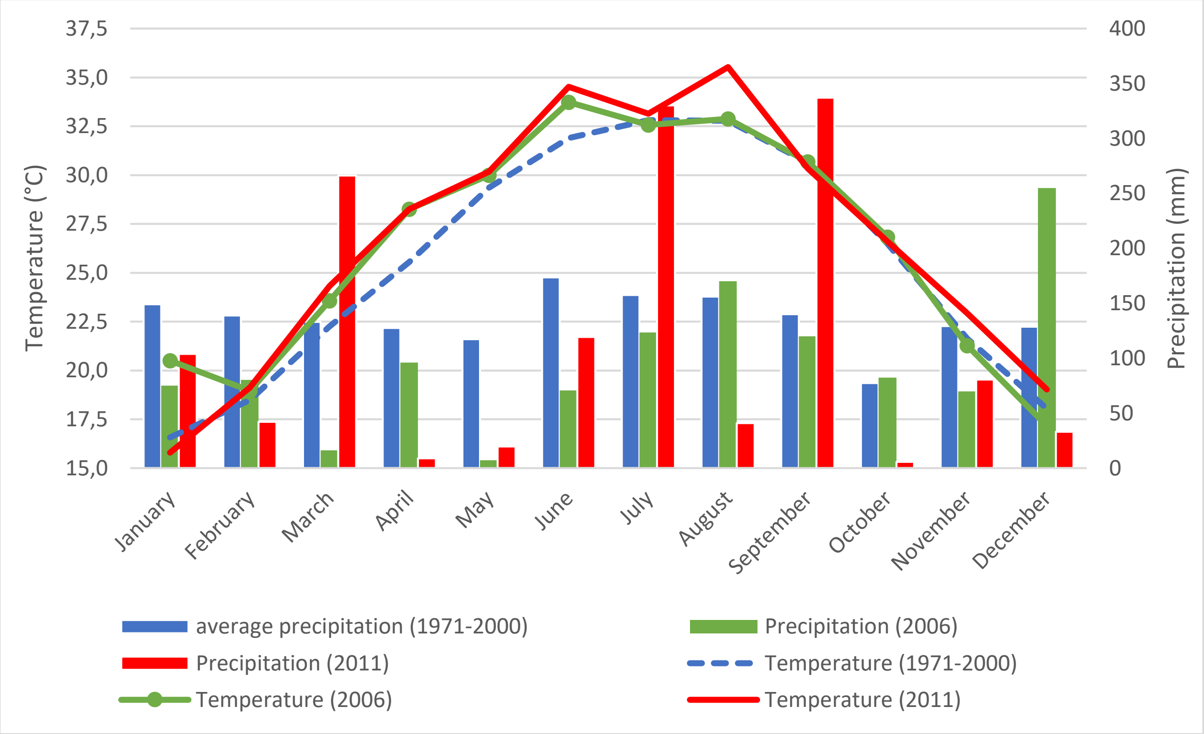


***Figure 4.4.4:* The average daily maximum temperatures per month and the monthly precipitation of in New Orleans during the drought years 2006 and 2011, compared with the average temperature and precipitation data of the period 1971-2000.**

4.4.4 Heatwaves

In New Orleans, every year there are one or more heatwaves using the Dutch definition (Annex N). The cumulated heatwave days are almost always above 150 days per year. With 203 heatwave days whereof 161 days were tropical in 2016 was most extreme. Furthermore, there is an increasing trend in heatwave and tropical days visible between 1948-2018.

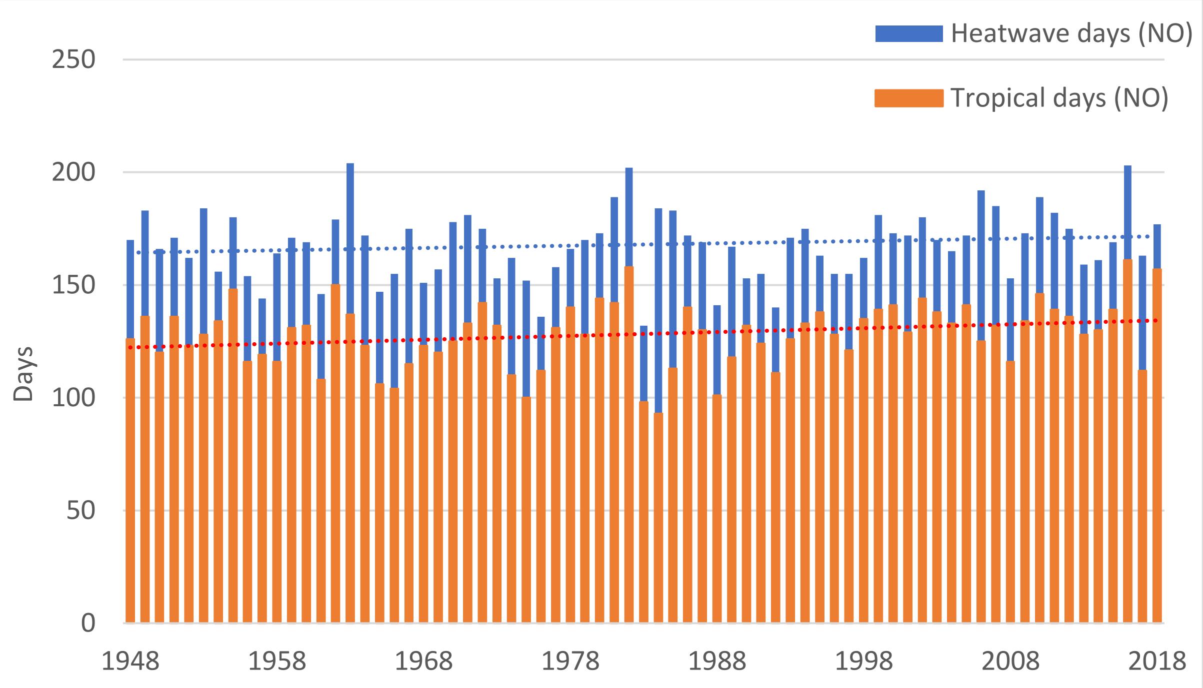


Figure 4.4.5. Cumulated number of heatwave days within a year (All days cumulated that satisfy 5 consecutive days or more above 25 °C of which at least 3 are above 30°C) and the cumulated tropical days (30°C or more) which has appeared within a heatwave in New Orleans. The trendline of tropical days is red dotted and the trendline of heatwave days are blue dotted.

4.5 Drought in combination with discharge Mississipi

The Mississippi discharges of the drought years 1963, 1976, 2000, 2006 and 2011 in New Orleans are displayed in figure 4.5.1. The lowest Mississippi discharge of 2100 m3/s (74161 ft3/s) was measured in November 4, 1939. Low discharge values normally occur at the end of the summer. During a drought, the discharges are below average except for 2011. Furthermore, discharges become below the low water reference plane at the end of September to December in 1939 and 1963. Noticeable is the extreme high peak of 45000 m3/s in June 2011. Meanwhile, there fell extremely little precipitation in the previous months. Which is one indication that meteorological drought does not always accompanied with hydrological drought.

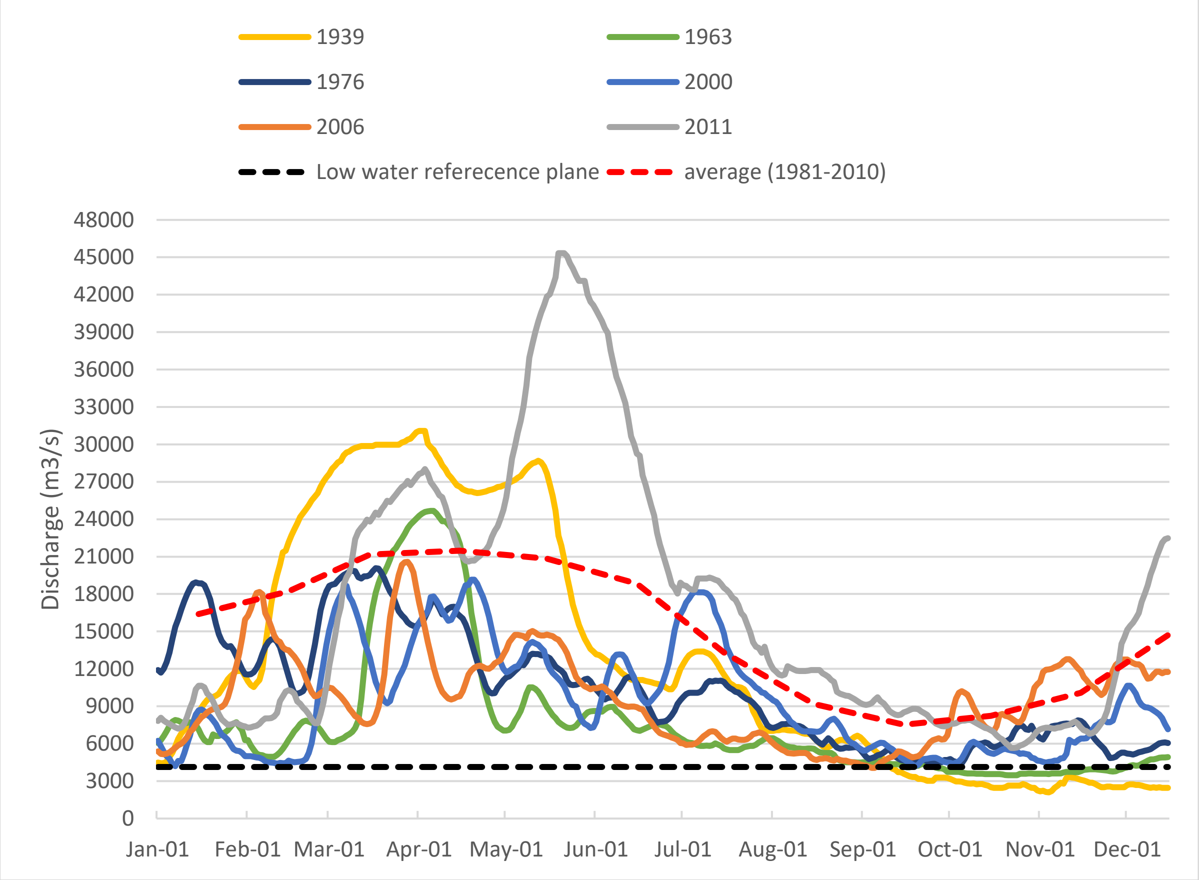


Figure 4.5.1: Lowest measured discharges of the Mississippi river at Tarbert Landing plus the monthly average discharge and the Low water reference line.

The relation between low Mississippi discharges with drought events in the county Orleans is visualized in figure 4.5.2 – 4.5.5. The first two figures show the relationship between PDSI and discharge deficits. During extreme drought (PDSI ≤ -4) from April to July, drought periods do correlate, with a discharge deficit above 5000 m3/s. However, the driest month (July 2000; PDSI: -6) had a normal discharge. Moreover, a high discharge deficit (>5000m3/s) appears also in wet periods in the county Orleans. From August to November there seems even less correlation in discharge deficits and PDSI than in the months April to July. This is because the change is higher that a larger part of the Mississippi catchment is in drought during spring and summer than at the end of the summer and Autumn resulting in more stable river discharges. Moreover, there is even less correlation between SPEI and low discharges of the Mississippi (Figure 4.5.4). Nevertheless, when we define drought as precipitation deficit, there seems a correlation between drought in New Orleans and low river discharges (figure 4.5.5).

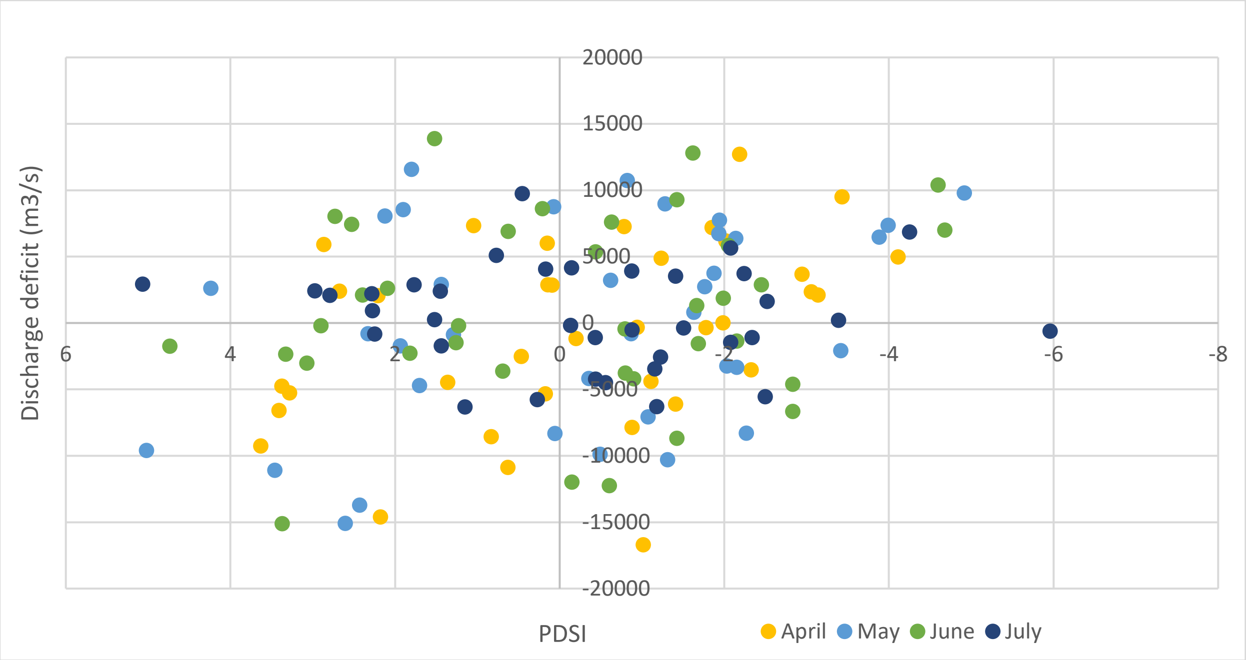


Figure 4.5.2: Discharge (Tarbert landing), PDSI values Orleans (1975-2010).

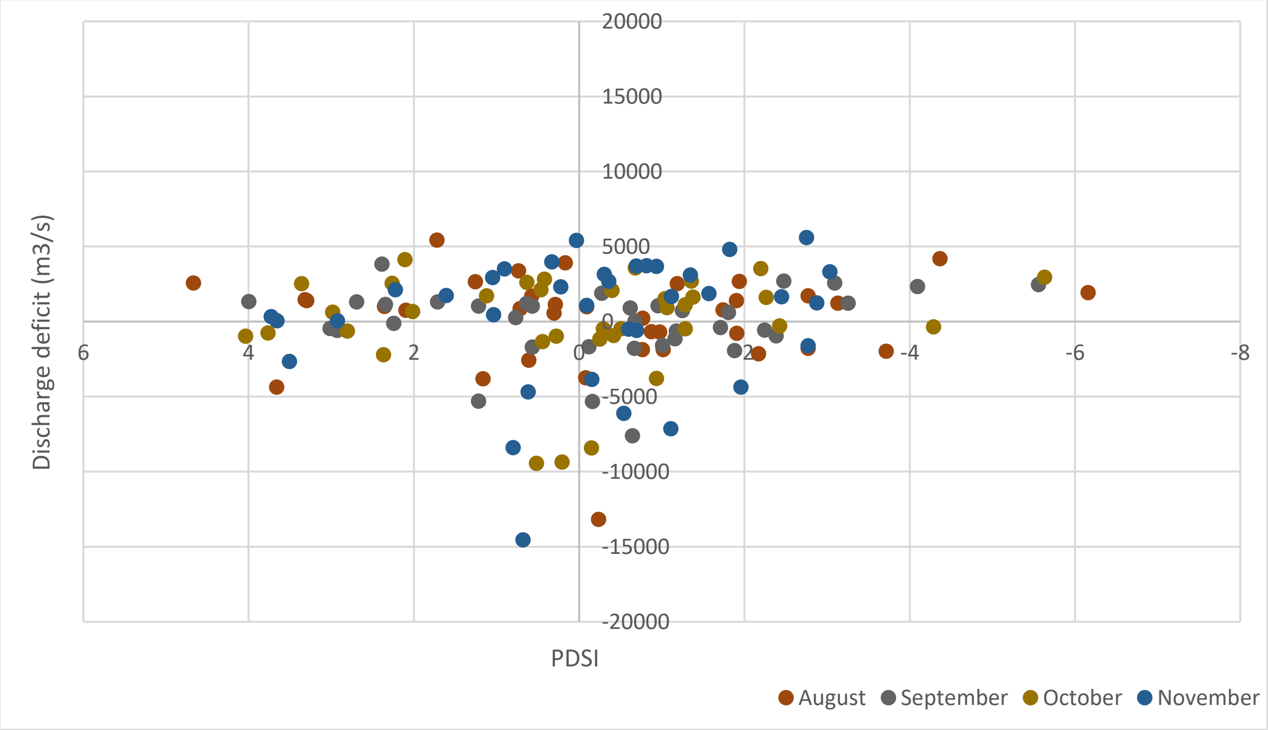


Figure 4.5.3: Discharge (Tarbert landing), PDSI values Orleans (1975-2010).

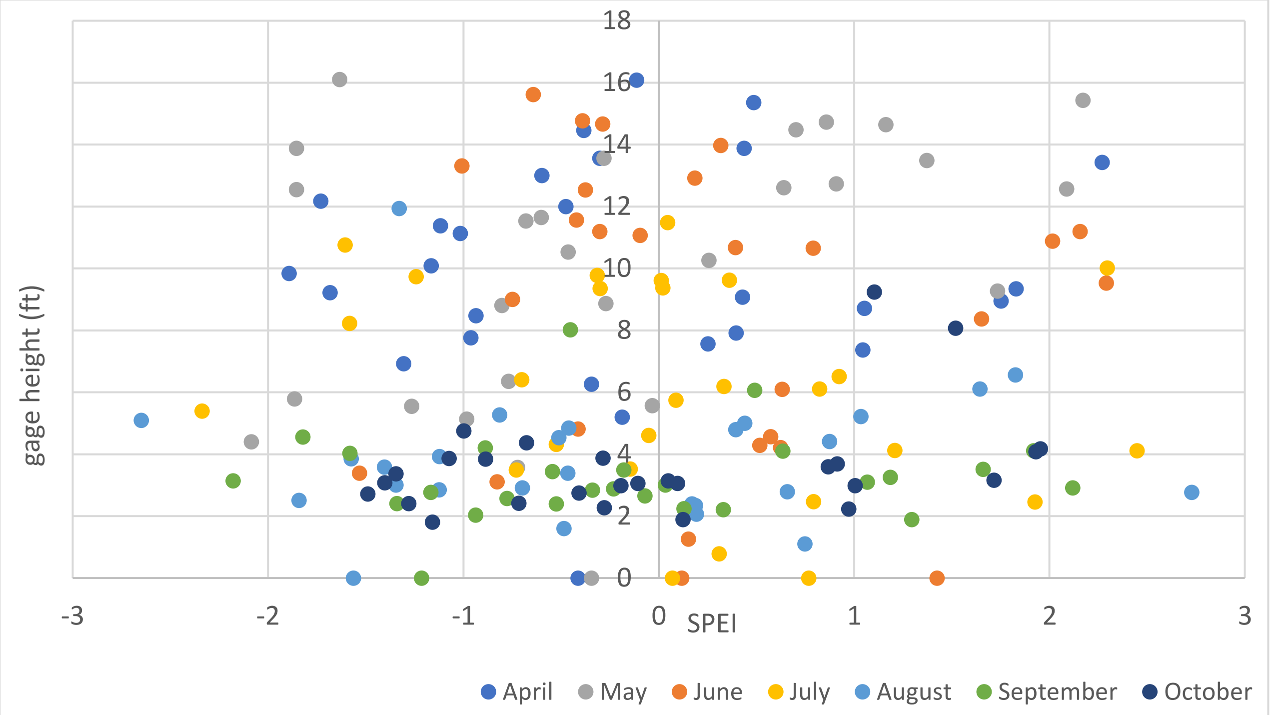


Figure 4.5.4 Correlation Gage height in Carrollton (New Orleans) and SPEI values of New Orleans.

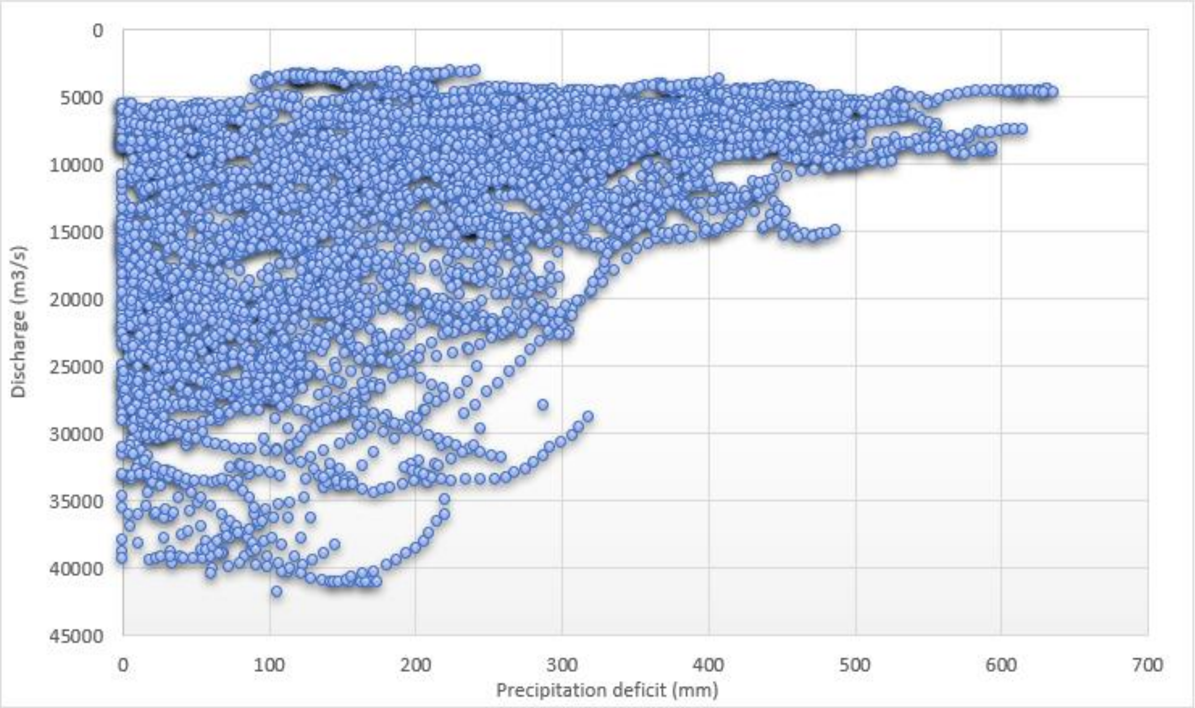


Figure 4.5.5 Correlation precipitation deficit based on the Dutch method with Mississippi discharges in the period 1961-1990 (April-September)

5. Results impacts drought and heat

5.1 Infrastructure

5.1.1 Roads

Drought

All damages are presented in table 5.1. Highways are affected by subsidence due to dehydrated peat and clay layers underneath the road in combination with long-term settlement processes, which may have been provided by desiccation in dry summers (Deltares, 2017). The resulted irregularities in the road surface appears often at the transition from paved parts with foundations such as bridges, tunnels and bins which are not affected by subsidence while the surrounding road will subside resulting in an undulating road (Figure 5.1.1). An additional result of subsidence are cracks in the asphalt. This process is accelerated due to large trees along the road which subtract all available water. This is most common at provincial and local roads. Furthermore, the rooting system expanse during drought which results in cracks in the road too. The same damages are observed at foot- and cycle paths made of asphalt or tiles which are prolapsed by subsidence and be lifted by growing tree roots (Figure 5.1.2; Van Joode, 2018). Besides, light weighted tiles of foot and cycle paths becomes loose due to dried out soils which poses a security risk (figure 5.1.3; Haarlems Weekblad, 2018). Recent examples are among other in Amstelveen and Haarlem in the summer of 2018.

Heat

Extreme heat leads to a decrease in the quality of the asphalt ("sweating/ melting") and track forming due to heavy traffic (table 5.2). In addition, heat also decrease the attention of road users (Deltares, 2017). Abroad a lot of damage is caused by the expansion of concrete structures. In the Netherlands bridges suffer a lot during heat periods because the metal of the bridge expands. As a result, the bridge can no longer open or closed (Watersportverbond, 2018).

Figure 5.1.1: Undulating road. Source: (Charlier et al., 2018)

Figure 5.1.2: tree roots damages the road. Source: (Van Joode, 2018)

Figure 5.1.3: Loose tiles due to dehydrated soils in Haarlem. Source: (Haarlems Weekblad, 2018)

Figure 5.1.4: Bridges are kept wet to prevent steal expansion. Source: (Watersportverbond, 2018)

5.1.2 Side road

Drought affects the instability of the road side mechanically by the growth of the root system and by soil processes due to moisture withdrawal. Furthermore, due to the dehydration of the soil, small animals living underground, like worms, are moving deeper in the ground to protect themselves for dehydration. Therefore, the number of voles, moles, rabbits and insects increase their activity searching for food which damages the root cover of the roadside and results in a lowering of the stability of the slope (Deltares, 2017). Another effect of vegetation along the road is the risk of fires in dry summers (figure 5.1.5; Sleutjes, 2018). This causes serious traffic disruptions. Furthermore, sideroad fires damages the root cover and therefor the quality of the slope of the sideroad.

Figure 5.1.5: Sideroad fire at the A58 highway. Source: (Sleutjes, 2018)

5.1.3 Railway

Drought

Railway embankments are vulnerable for drought and are additionally checked for impending subsidence. In addition, roadside fires pose also a threat (figure 5.1.6). One spark caused by the braking of a train could start a fire which may results in long train delays (NHnieuws, 2018).

Heat

At temperatures above 25 °C, the railway can reach 70 °C. Steel of the railway and rail bridges expands resulting in twists and turns in the track (figure 5.1.7). If the rails cool down at night, there is a chance that the track will crack. Such a 'rail splash' causes derailed trains (NOS, 2018). In addition, electronics are also sensitive to heat causing signal and switch failures (NHnieuws, 2018). This results in major delays.

Figure 5.1.6: side road fires along the rail track. Source: (Eg, 2013).

Figure 5.1.7: If outside temperature rises above 25 °C, the railtrack could be heat up to 70 °C causing rail buckling. Source: (Prorail, 2015).

Table 5.1: Drought damages road, side road and on the railway

Infrastructure	Impact
Highway	Undulating road
Provincial roads	Local subsidence cracks
Local roads (tiles)	Prolapsed Loose tiles Cracks
Side road	Slope instability Side road fires
Rail way	Subsidence railway embankment Side railroad fires

Table 5.2 Heat damages on infrastructure

Heat	Impacts
Asphalt	Melts Track formation
Bridges	Not able to open or close
Railway	Electronic failures Expansion of the railroad (rail buckling)

5.1.4 Underground infrastructure

The alternation of falling and rising groundwater levels to near or below drainage level due to dry and wet periods results in differential subsidence (shrink & swell). This are causing damages to drainage, sewage, water, gas pipes and cables and will shortens the lifetimes or necessitates a higher maintenance frequency (Brolsma, 2012; Table 5.3). Furthermore, the impacts of clogging are expected to be exacerbated due to more frequent extreme drought periods in the future.

Table 5.3 Drought impacts on underground infrastructure

	Result 1	Result 2	Result 3
Drainage system	-Clogging due to iron oxidation and due to growth of the tree root system		
Demolition of house connections	- Leakage in crawl spaces - Water nuisance - Odor nuisance - Gas explosion risk - Unwanted drainage		
Broken pipes (Cracks and collapse of underground sewerage)	- Leakage of sewerage - Unwanted drainage function - Creation of dead storage in lowered pipe sections	- Lowers the groundwater level - Drains too much groundwater into the sewage treatment plant. - Influx of sand from the roadcunet -Breeding place insects	- Damage the road (subsides, cracks, holes)
Drinkwater pipes	-Breaking	- Street Flooding - Bacteria and pollution could enter the water system => Risk human health	
Pipelines in general	Decreasing cathodic protection of pipes due to changing soil moisture content		

5.1.5 After drought period

The first rain after drought causes slippery roads and street flooding. This because hardened surfaces are temporarily containing more heavy metals, rubber, dust, oil residues, petrol residue and organic material (early leaf fall) in dry periods. This becomes a viscous residue in combination with water and creates slippery roads (figure 5.1.8). Additionally, more sewage sludge is temporarily supplied to the treatment plant and in the case of extreme precipitation after a drought there is more risk of overflows (Brolsma, 2015). Negative effects are: decrease water quality, odour, increased pollution burden, lack of oxygen in the water and mortality of aquatic organisms.

Figure 5.1.8: Viscous residue after the first rain after drought causes slippery roads

5.2 Buildings

5.2.1 Isolated Footing/ Combined footing

The foundation is usually built on sand layers whereby the walls are through the intervention of a widened foot (made of concrete), rests directly on the load-bearing soil. Drought damages are differential subsidence and cracks in walls. This appeared in the dry summer of 2006 and in 2018 in Zevenaar (Stuurman, 2019; figure 5.2.1-5.2.3). In this village, groundwater levels dropped drastically due to consistent drought and trees started to subtract water from clay layers. As a result, houses become under strain due to settling of dehydrated soil. The effects are often not direct visible and can occur years after the drought period when heavy soil vibrations are made by building new houses or when heavy traffic drives by causing little shock waves in the subsurface.

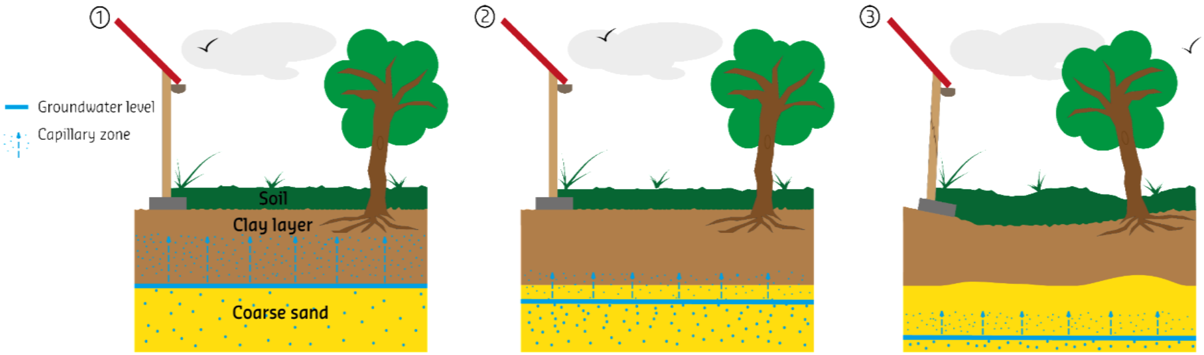


Figure 5.2.1: The process of subsidence of a house when groundwater levels are dropped, situation in Zevenaar. Source: (Stuurman, 2019)

Figure 5.2.2: As a result of land subsidence, two houses have been stabilized to prevent collapsing. Source: (Schreuder, 2018)

Figure 5.2.3: Tearing in walls as a result of land subsidence in Zevenaar. Source: (Opten, 2018)

5.2.2 Wooden foundation Piles

Wooden pile foundations are applied for hundreds of years for houses, churches, factories, quay walls, bridge heads and other objects to give them solid foundation on sand layer below the soft soil (clay or peat) in West and North Netherlands and around rivers. Large cities like Amsterdam, Rotterdam, Haarlem, Dordrecht and Zaanstad are for a large part build on wooden piles. By low groundwater levels during drought or due to broken sewage pipes, the upper pile sections regularly rise above the water and reacts with oxygen resulting in pole rot by soft rot fungi (Brolsma, 2012; Figure 5.2.4). Even though this slowly process, multiple periods from drought can be added up leading to visible damages (cumulative dry stand; Vereniging Eigen Huis, 2018). In addition, in a becoming warmer and dryer climate, the wooden foundation will be exposed longer to dryness in a year. This may result in an accelerated degradation whereby bearing capacity of the foundation decreases and leads to subsidence of the building. Currently, there are about 800.000 houses at risk to differential subsidence due to pole rot, especially in the old neighbourhoods (Figure 5.2.6; De Leeuw, 2018). Another impact of lower ground water levels and dehydrated soils is negative adhesion caused by the increase in grain tensions in clay layers or by oxidation of peat during drought (Figure 5.2.5; SHR, 2015). Both, negative adhesion and pole rot can cause differential subsidence and cracks in walls of buildings.

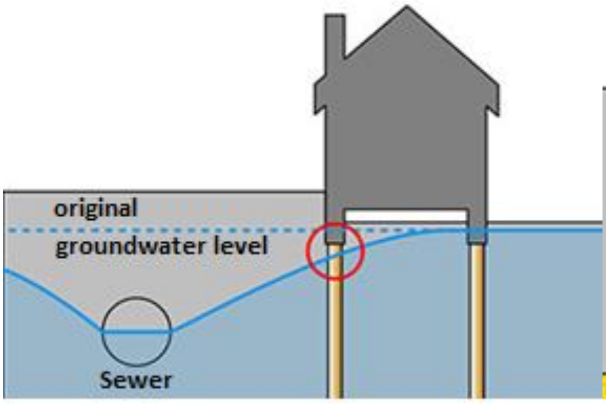


Figure 5.2.4: Lowered groundwater levels exposing wooden pile to oxygen causing pole rot. Source: (Paalrot.info, 2019)

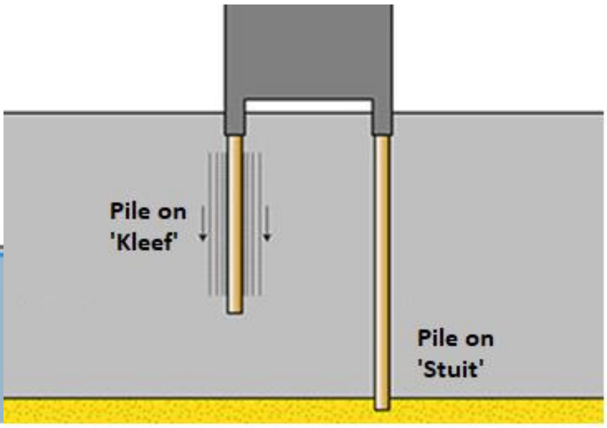


Figure 5.2.5: Negative adhesion "kleef" pulls the foundation pile below resulting in foundation damages. Stuit: when the foundation pile is resting on stable sand layers. Source: (Paalrot.info, 2019)

Figure 5.2.6: Areas at risk for subsidence of houses. Source: (Messelink, 2018)

5.2.3 Concrete slab

This type of foundation is made of a double-reinforced (top and bottom) concrete slab of at least 30 cm thick over the entire surface of the building, provided with a concrete edge which reaches to the frost-free depth (minimum 80 centimetres). In general, it is built on low load bearing and horizontally uniform layered surfaces (LSY consultants, 2017). In dry summers and due to drainage of nearby land, ground water levels will drop in the area resulting in shrinkage of the clay. In the case of uniform settlement, the building will be subsided entirely (Figure 5.2.7, left). If the layers are not uniform or horizontal, subsidence causes tilting of the house (Figure 5.2.7, right). Usually, no cracks will be formed in the walls.

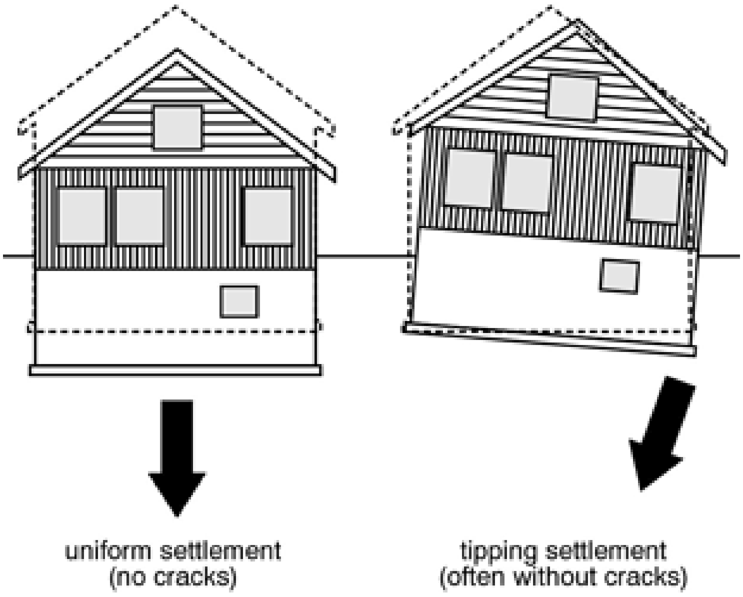


Figure 5.2.7: Concrete slap foundation, types of settlement. Source: (LSY consultants, 2017).

5.3 Peat & clay levees

Dehydration is the main risk for peat levees during drought (Table 5.4). Due to the drop of surface and ground water levels, peat layers will become in contact with air causing peat oxidation. Furthermore, the water content of the peat below the phreatic line decreases. This leads to a reduction of the shear resistance. Both processes lead to a volume reduction and forms large shrinking cracks in the quay. In the worst-case scenario, the water pressure against the levee becomes too high or the downward water pressure will become smaller than the upward pressure in the underlying sand layers (Deltares, 2018c). As a result, the dike could start to shift and causes a flooding like in Wilnis in 2003 (figure 5.3.1). Vegetation increases the rate of dehydration of the quay as well. Especially trees, which evaporates twice as much as grass (Akker, 2018). In dry circumstances, trees expand their root system and take up all available groundwater. Due to this, the soil may dry out meters deep and could cause large cracks and local subsidence. If the cracks are large enough, it damages nearby roads with shallow foundation. However, vegetation of a good quality is important on a levee because it stabilize the dike. Especially grass which have a relatively low evaporation rate and a tight rooting system. In drought periods, dehydration and fires could damage the grass and decreases the erosion resistance which results in instability of the levee. Also, rain could lead to instability of the dike when precipitation flows into the shrinking cracks. Furthermore, drainage and dry summers increases inland subsidence resulting in an increased hydraulic head difference. In addition, the levee becomes relatively higher and needs more maintenance (Deltares, 2018c). Furthermore, most classified peat levees are clay levees on peat layers (Akker, 2018). This type encounters the same drought damages as peat levees. The main difference is the clay weight loss due to dehydration is less than for peat.

Figure 5.3.1: Dike breakthrough Wilnis. Source: (Deltares, 2018c)

Figure 5.3.2: Cracks due to dehydrated soil. Source: (Deltares, 2018c)

Table 5.4 Peat/clay Levee impacts

Impacts	Cause
Shrinking cracks	Drought, evapotranspiration & increased rooting
Stability decrease	Increase difference hydraulic heads, peat and clay oxidation, water enters the cracks, water abstraction due to trees, dehydrated vegetation, cattle and fires

5.4 Nature

5.4.1 Rivers

Drought impacts are showed in table 5.5. Water levels decreasing during drought leading to negative effects for the economic sector, because inland navigation becomes limited due to insufficient sailing depth. Furthermore, the so-called salt spike increasingly penetrating the hinterland. Therefore, locks are opened to a limited extent which causes delays for shipping. Due to low water, inland navigation led around 200 million euros of additional costs in the Netherlands in 2003 (Peters, 2004). Another effect of low river discharge is the decrease of the water quality. There is less river water to dissolve harmful substances. Therefore, the concentration of medicines and other pollution in rivers will increase. This will lead to higher water treatment costs to drinking water companies. Effects of climate scenarios (2050) at drinking water intake points is showed in annex O. Furthermore, when river water levels exceed the 23 °C, the so-called "cooling water limitation step-by-step plan" comes into action. This plan implies that cooling water may not exceed 30 ° C when it is discharged into the river. This leads to an impaired production/shut down of thermal and nuclear powerplants. In addition, electricity prices may increase because low river discharges disrupt the coal supply.

Table 5.5 River drought impacts

	Impact	Effect
Rivers	Transport stagnation	Economical losses
	Limited freshwater supply	Drinkwater/ irrigation water scarcity
	Saltwater intrusion	Salinization
	Higher concentration of pollutants and medicines	Higher drink water treatment costs
	Warm water	Cooling water discharge limitations

5.4.2 Lakes, canals and small streams

Due to the lack of flushing possibilities, the water quality of lakes, canals and small streams decreases during drought and heat (table 5.6). Especially the quality of shallow stagnant water decreases rapidly. This is partly due to the drop of oxygen levels in the water caused by the decrease of solubility of nitrogen during high temperatures and the degradation of organic matter by bacterial activity which results in odour nuisance. Furthermore, the waters in urban areas are almost always eutrophic and therefore easily affected by algal blooms and duckweed in warm periods. A subsequent result of low water (Figure 5.4.1), low oxygen levels and high-water temperature is the increasing fish mortality.
Furthermore, during warm periods, blue algae grows in stagnant water like lakes and ponds (between april to October; Figure 5.4.2). The optimal growing conditions are water temperature of 20°C to 30°C. Blue algae produce toxins like microcystines and neurotoxines. Different symptoms are visible when someone comes into contact with these toxins such as nausea, skin irritations and diarrhea, and in extreme cases, mortality. Research in de Nieuwe meer showed, when water temperature increases 1.9°C (extreme summer of 2003) led to 385% more blue-green algae, compared to an average summer (Jöhnk et al. 2008). Another harmful toxin is Botullinum caused by the bacteria 'Clostridium botulinum'. The bacteria grow in a protein-rich and oxygen-poor environment with a water temperature of 20 °C. Especially water birds and fish die as a result of this toxin. Botullinum is not dangerous for humans but other pathogenic bacteria which may grow in the dead fish could form a risk for human health.

Table 5.6: Heat impacts on small streams and lakes

	Impact	Result
Small streams/lakes	Oxygen decline	Fish mortality
	Odour nuisance	
	Blue algae	Health risk
	Botulism	Health risk
	Increase algae bloom	Oxygen in water declines
	Swimming water quality declines	Health risk

Figure 5.4.1: dried out small streams. Source: (omroep Gelderland, 2018)

Figure 5.4.2: Blue algae in Hoornse Meer. (Source: Dagbald van het Noorden, 2017)

5.4.3 Vegetation

Drought

Trees increase soil dehydration rates leading to drought stress on vegetation (table 5.7). A general tree which is planted along the road consumes around the 50-70 litres per day. In addition, a mature oak or beech uses 150-300 litres per day and a poplar tree extract 1500 litre per day from the soil (Groenwelzijn, 2016). If water levels drop very quickly, vegetation are not able to take up enough water and they absorb fewer nutrients. In addition, stomata are closed to limit evaporation during warm circumstances, which limits the assimilation (and growth) and vitality of the vegetation (Deltares, 2012).

The first indication of drought stress is withered grass (Figure 5.4.3). Grass becomes yellow because grass is not able to take up enough water during dry periods due to shallow rooting. Drought mainly affects young plants (<3 years), they have shallow rooting and needs sufficient water for growing. Older vegetation is also vulnerable for drought. However, trees and other vegetation have protecting systems against drought. First, leaves become yellow and start to fall (figure 5.5.3 & 5.4.4). This is most common to Linden, Poplar trees and Hornbeam. The oak does not drop its leaves during a drought because the deep root system absorbs groundwater from deep soil layers for a long time. Nevertheless, the rooting of trees in urban areas are usually not going deeper than 1 meter. The second protection is premature fruit fall which limits the water consumption of the tree. If drought consists, the tree bark will tear and falls off. This phenomenon is caused due to extreme dry and warm conditions and is well known for Mediterranean trees. For example, the sycamore tree (Platanen; Figure 5.4.5. This is a typical Mediterranean tree which also grows in the Netherlands. If these trees lose their bark, it is a sign of growth (Verburg, 2018). However, in the Netherlands, other trees show the same behaviour which damage the tree. Furthermore, vegetation that subjected to drought stress in combination with heat are having an expected increase in secondary infestations. As example, vegetation becomes more susceptible for honey fungus, giant fungus and certain tree bark diseases (Brolsma, 2012). At the end, a part of the vegetation may die due to drought stress.

Salinization affects the vegetation too. Due to the greater precipitation deficits and a decreased water supply from the IJsselmeer and the Rhine during meteorological and hydrological drought, leads to fewer options to flush fresh water into coastal regions. Therefore, saltier water must be introduced into the regional surface waters to prevent damage to flood defences and subsidence. As a result, groundwater and soil moisture become more saline and may threaten most vegetation.

Lastly, many Eco-passages are built over highways to connect different nature reserves to each other (figure 5.4.6). Vegetation on the Eco-passages are highly vulnerable to dehydration during dry periods because little water can be stored in the 50 cm deep soil.

Figure 5.4.3: Withered grass and leaves become brownish

Figure 5.4.4: withering trees, leaves become brown and will fall off

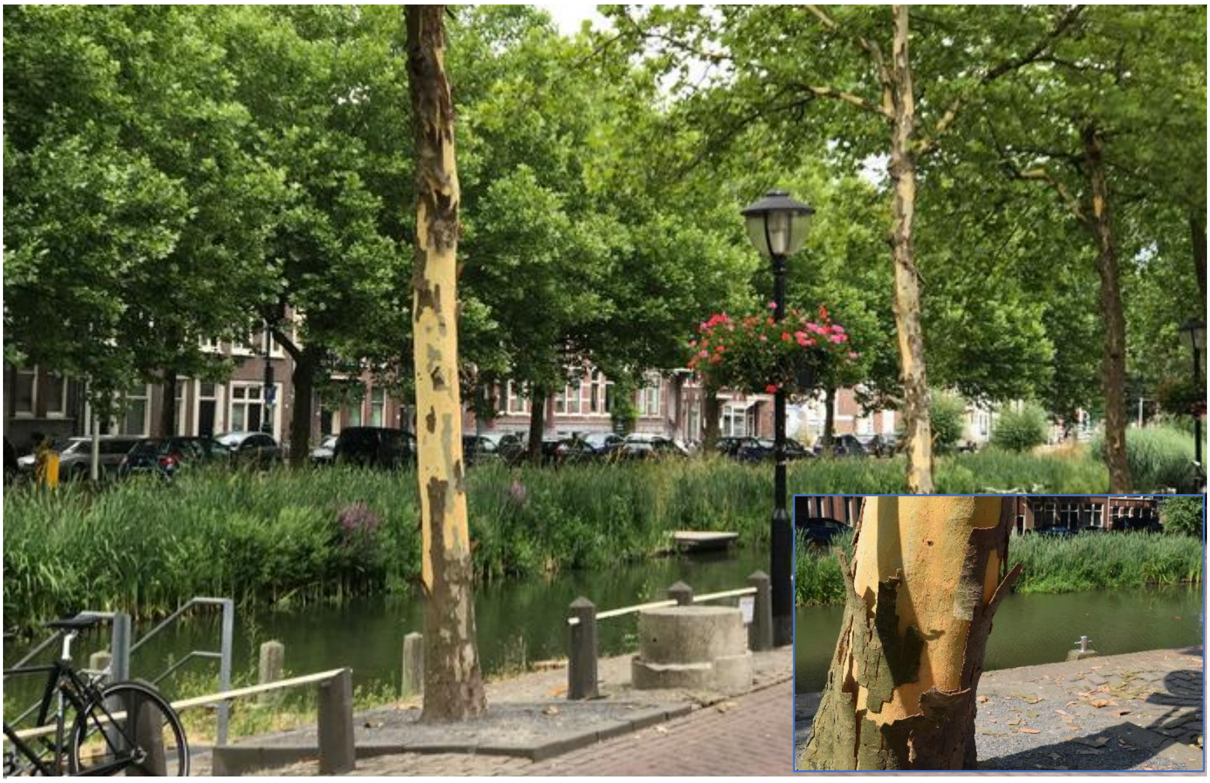


Figure 5.4.5: Sycamore trees losing their bark due to drought at de Nieuwekade, Utrecht. @ Ronnie Hendriks

Figure 5.4.6: Eco passage Waterloo. Source: (Niessen, 2018)

Table 5.7: drought impact on vegetation (NL)

Impacts
- less vital
- Leaf fall
- Fruit fall
- Tree bark release
- Withered grass
- Plant diseases
- Soil acification
- Secondary infestations

Heat

A warmer climate leads to changes in species composition of organisms living on trees and shrubs which can bring new diseases. Furthermore, higher temperatures in combination with enough water availability will enlarge the growing season and growing rate. This leads to additional required maintenance costs. For lawns, it means one or two (5 to 10%) more mowing operations. Besides, the hay fever season will be longer (Brolsma, 2012).

Table 5.8: Heat impacts on vegetation

Heat NL	impacts
Growing faster (temp+moist)	- More maintenance
Longer growing season	- Longer hay fever season
Change in species	- New diseases can occur

After drought

Roots of trees have grown to the lowest average groundwater level. If groundwater levels rise, trees could drown.

5.4.4 Animals

During severe drought, large animals like deer, roe deer, boar and highlanders have a shortage of drinking water because water pools can dry up completely (Figure, 5.4.7; Peters, 2004). Other problems of low water levels and high temperatures is the increasing mortality of fish and freshwater mussels (Peters, 2004). Furthermore, the habitat of black-tailed godwits in peat meadow areas decreases. However, Night blacks and some butterflies (the royal page) are doing well during high temperatures (Peters, 2004). In addition, warm weather leads to a population increase of insects such as the harvest bug, oak processional caterpillar (Figure 5.4.8) and mosquitos which causes public health risks (chapter 4.5).

Figure 5.4.7: A deer drinks last water from dried out pool at the Hoge Veluwe. source: (De Volkskrant, 2007)

Figure 5.4.8: Oak processional caterpillar

5.5 Human health

High temperatures have negative consequences on human health (table 5.9). Heat stress appears when the human body is not able to lose enough body warmth by blood vessel dilation and sweating. As a result, four different forms can be distinguished (howe & boden, 2007). Older people and people with respiratory diseases and persons with cardiovascular disease are more sensitive for heat stress (RIVM, 2014). Other vulnerable groups are young children, medicine users, obese, drugs and alcohol users and people who are working or living on the street. During extreme heat hospital admissions increases (Döp, 2011). Most admissions are kidney disease by older people due to dehydration and respiratory disease due to presumably more bacterial or viral infections or due to the increase of ozone and particulate matter in the air. Furthermore, periods of sustained heat increase death rates by 12% in the Netherlands (40 deaths per day; Döp, 2011; figure 5.5.1). In addition, high temperatures at night influences the sleep quality which leads to exhaustion, lack of concentration and may decline the labor productivity resulting in potentially dangerous situation in traffic or at work. Furthermore, people may become more aggressive.

Other impacts of heat are the increase of the hay fever season resulting in more allergens such as pollen, dust mites, and fungal spores in the air (RIVM, 2014). Furthermore, heat will increase the prevalence of vector-borne (mosquitos), waterborne and foodborne infectious diseases (RIVM, 2014). Recently, 9 million euros has been made available for research to combat tropical diseases transmitted by mosquitoes (Tates, 2019). At this moment, no diseases are transmitted by mosquitoes in the Netherlands (RIVM, 2019). However, climate change will introduce the Aedes Aegypti (denquemug) and the Aedes Albopictus (aziatische tijgermug) which brings diseases as Denque, Chikungunya, Zika and West Nile virus (van den Brink, 2019). In Addition, yearly 80.000 people get health complaints from the oak processional caterpillar (Jans, 2012). Resulting symptoms are skin rashes and eye and airway complaints (RIVM, 2014). Furthermore, warmer temperatures increase the harvest bug population which lead to an increasing risk to the Lyme disease.

The experience of heat becomes enlarged in cities because urban areas are extra heating up and cool down less at night due to the urban heat island effect. Furthermore, air pollution and smog increase due to higher concentration of ozone (O3), particulate matter (PM10) and nitrogen dioxide (NO2) in the air during a warm period. These events are possibly responsible for around 25 to 40% of the observed excess mortality in the very hot summer of 2003 (RIVM 2014).

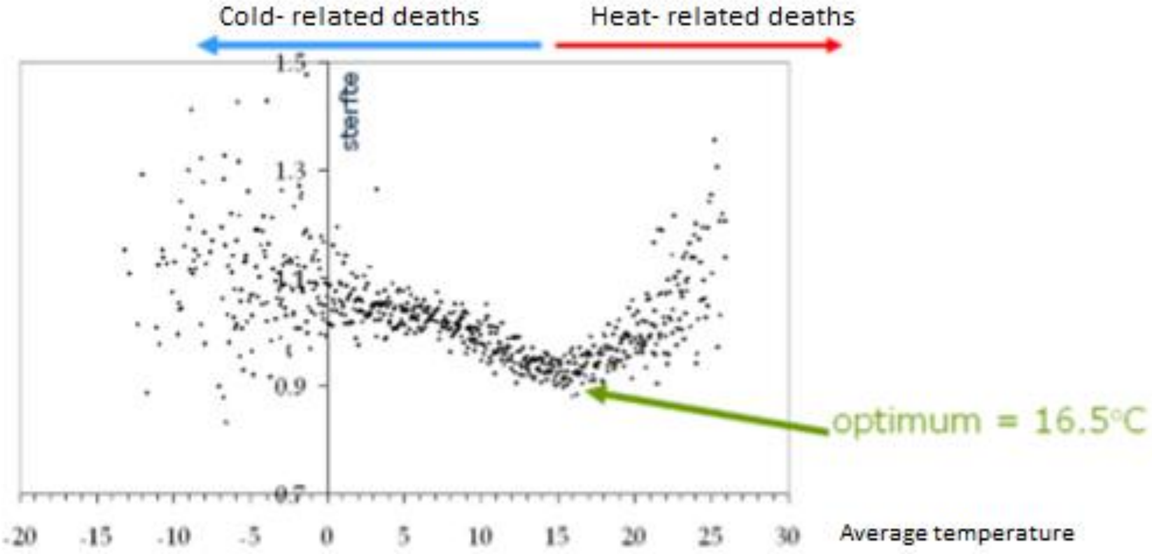


Figure 5.5.1: Relation between the average day temperature (°C) and mortality in the Netherlands. source: (Döp, 2011)

Table 5.9: Consequences of high temperatures on human Health

Impact	result
Heat stress	- Heat rash - Heat exhaustion - Heat cramps - Heat stroke
Human behaviour	- Lack of concentration - More aggressive - Decline labour productivity
Allergens (longer season)	- Hay fever - Dust mites - Fungal spores
Other public health risks	- Vector, water, food borne infections - Oak processional caterpillar - Harvest bug - Water quality decline - Air pollution

6. New Orleans Fieldwork

During visiting New Orleans, temperatures and humidity rates were high and the experienced amount of precipitation was high and intense. According to the interviews, it appeared that no major drought periods and related damages were known. However, while driving through the city, there were damages that could have been caused by drought.

6.1 Houses/ foundation

Many houses are built on high pales for flood prevention, sometimes 10 ft high. Therefore, most houses have stairs to get to the front door. Most common foundation types are pillars and concrete foundations. Drought impacts on houses are displayed in table 8.1. Heat impacts are often the contraction of wood (many buildings are made of wood in New Orleans) resulting in leakage in houses after a drought period.

Table 6.1 drought impacts on houses

Cause	impacts	Figure
Shrink and swell	Doors sticking	-
	Gaps between windows and doors	-
	Cracks in foundation	6.1.1
	Cracks in walls	6.1.2
	Outside stairs subsides	6.1.3
	Driveway subsides	-

An example, to prevent houses for shrink and swell impacts are told by Eric Eagan (Gen. Taylor Street). He noticed that his front door was sticking and within several days it could not lock at all. If he wanted to fix it by a company, he needed $3,000 worth of shoring work. However, someone told a much cheaper solution. The problem occurred due to soil compaction because of drought. Therefore, he watered the soil under his house for 36 hours. At the end, the problem of sticking doors was solved (Bruno, 2016).

Figure 6.1.1: Cracks in foundation (N Rendon St/ Bienville St; Bayou St.John)

Figure 6.1.2: Cracks in walls (St. Anthony)

Figure 6.1.3: subsidence of front door stairs (St. Anthony)

Architects take little account of drought and heat events into the design of a building. Otherwise, they mentioned, houses become too expensive for the citizens and almost every household use air-conditioning nowadays. However, historic buildings were made to handle heat without air conditioning. The so-called Pitot houses (Figure 6.1.4). The main characteristic is the large balcony which covers 50% of the living space. This provide people enough shadow to live most of the time outside the house to avoid overheating.

Figure 6.1.4: Pitot House; Adress: 1440 Moss St, New Orleans, LA 70119, U

6.2 Infrastructure

Damages to the infrastructure are similar to the Netherlands (table 5.1-5.3 & 6.2). In general, shrink and swell causes most damages to the infrastructure which leads to unsafe roads and broken pipelines.

Table 6.2: Observed infrastructural drought damages in New Orleans

Impacts	Result	Figure
Cracking roads	- Unsafe roads	6.2.1
Subsidence roads	- Bumpy roads	6.2.2-8.2.3
Broken drink water pipes	- Street flooding	6.2.4
Broken sewage systems	- More land subsidence due to lowering groundwater levels	6.2.5/6.2.6
Broken house connections	- Leakage & Gas explosion risk	-

Figure 6.2.1 Cracking road (Lower Garden District'; Felicity St/ Richard St)

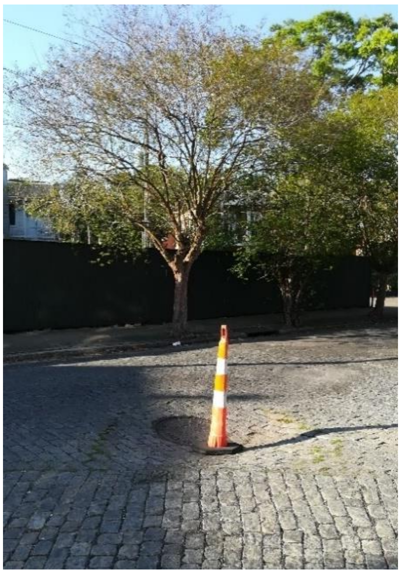


Figure 6.2.2 road subsidence (Lower Garden District; Chestnut St/ Felicity St)

Figure 6.2.3: around paved structures the road has subside (St. Anthony, London Avenue outfall Canal)

Figure 6.2.4: Broken water pipes causes street flooding (St. Anthony; Burbank dr)

6.2.5: Indication of land subsidence (New Orleans)

Figure: 6.2.6: Overview of a road which has partly subside and partly repaired (St. Anthony, Warrinton Dr)

6.3 Vegetation

During the walking tour ''plant ecology'' (2019, March 29; Annex P), there was no sign of drought and heat stress on nature. Native species are adapted to withstand heat and drought periods. Bigger issues for vegetation are future sea level rise and salinization. However, the soil in some parks were dried out (figure 6.3.1). Moreover, sprinkling systems were installed in many private gardens especially in wealthy areas (Lower garden district). Furthermore, Ecologist J. Lewis mentioned that there were drought impacts on vegetation, especially at the end of winter (Table 6.3). *''Excessive heat and lack of rain have affected more than merely the gardens*''. In addition, Audubon Park irrigates with groundwater. This is Iron rich (which consumes oxygen) and saline. Moreover, City Park uses water from the Bayou (brackish water) during drought (Buchanan, 2011). Furthermore, oxygen levels drop in water due to excessive plant growth in warm conditions.

6.3.1 Raingardens

Currently, green infrastructure is a hot topic to reduce heat impacts. Especially raingardens get a lot of attention (Figure 6.3.2). They are designed as low- lying gardens which should collect water from roads, rooftops and other hardened surfaces preventing streets from flooding during rainfall. How these gardens perform during drought is not known. However, they are watered in the first year (figure 6.3.3-6.3.4).

Table 6.3: drought and heat impact on the vegetation

Impacts	When/where
Dried out soils	During drought
Premature leaf fall	Often before spring
Grass and leaves become brownish	Winter
Cyprus tree: premature needle fall	Significant dry periods (not often)
Raingardens dry out	Open places
Swamp & marsh fires	2011

Figure 6.3.1: dried out soil at Audubon Park

Figure 6.3.2: example of a raingarden in St Bernard avenue/ Milton street

Figure 6.3.3: Irrigation systems in raingarden at parking City park

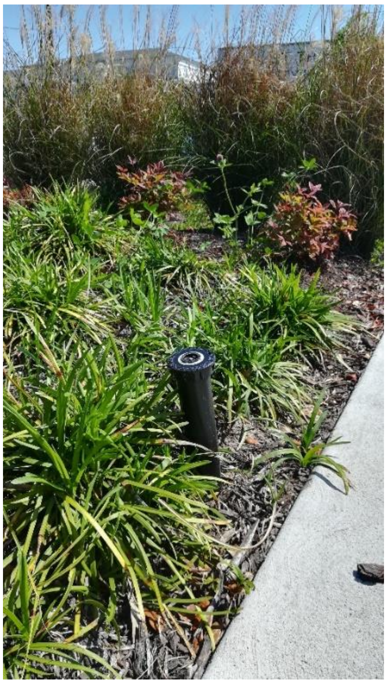


Figure 6.3.4: Irrigation systems in raingardens at St Bernard ave/ Milton st.

6.3.2 Swamps

The transitioning from swamps to marchlands and open water is among other due to severe drought and salinization. Research to the decline of the Maurepas Swamp (second largest contiguous coastal forest in Louisiana) measured during periodic droughts (2000 & 2006), salinity levels above 10 ppt for extended periods in Lake Pontchartrain and in Lake Maurepas (Shaffer et al., 2016). During the drought of 2000, salinity levels reached 10-12 ppt in the LaBranche wetlands (close to Lake Pontchartrain; figure 6.3.5). This leaded to substantial mortality to bald cypress.

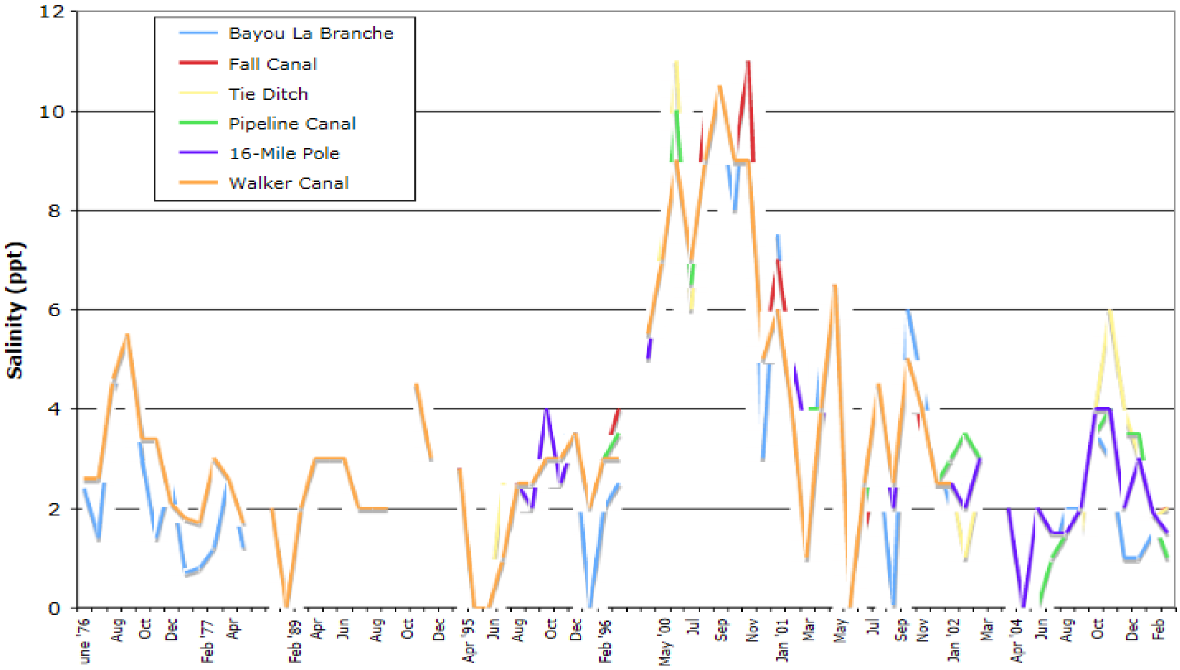


Figure 6.3.5. Surface water salinity in the LaBranche wetlands from June 1976 through February 2005. Source: (Shaffer, 2016)

Another result of droughtare the peat fires in Easter New Orleans which was possibly started due to a lightning strike in August 2011 (Schleifstein, 2012). This fire last for months burnt 4.27 square miles of swamp land down Figure 6.3.6). The smoke consisted small particles which led to health risks in the entire New Orleans area.

Figure 6.3.6: David Grunfeld, The Times-PicayuneThe New Orleans Fire Department fights the underground fire in eastern New Orleans on Jan. 17 by pumping water from a nearby canal to the site using a 6-inch fire hose. Source: (Schleifstein, 2012)

6.4 Human Health

6.4.1 Heat Island

In the United States, heat is the number one weather-related killer (New Orleans Health department, 2018). In New Orleans, the combination of high humidity and extreme heat which returns every summer creates difficult living conditions. In general, heat impacts on human health are similar as in the Netherlands (Chapter 5.5). However, New Orleans experiences longer and higher temperatures. Figure 6.4.1 shows the areas, where temperatures are relatively higher due to dense housing, paved surfaces and a lack of tree cover (Figure 6.4.2). These high temperatures affect among others the sleep quality. In 2016, there were 43 nights in a row, temperature exceeding 26,7 °C (80°F) which is the sleeping safety line of indoor heat (New Orleans Health Department, 2018). In addition, according to Chang, extreme heat causes a spike in crime and increases suicide rates.

The most vulnerable people for heat stress is the 27.7% of New Orleanians which are living in poverty whereof 1,703 residents are homeless (New Orleans Health Department, 2018). Furthermore, approximately 1.25% of New Orleans households did not have air conditioning in 2011 and others are not able to pay the high electricity bill or don’t have the knowledge to take precautions to protect themselves to extreme heat (lack of education or language barriers).

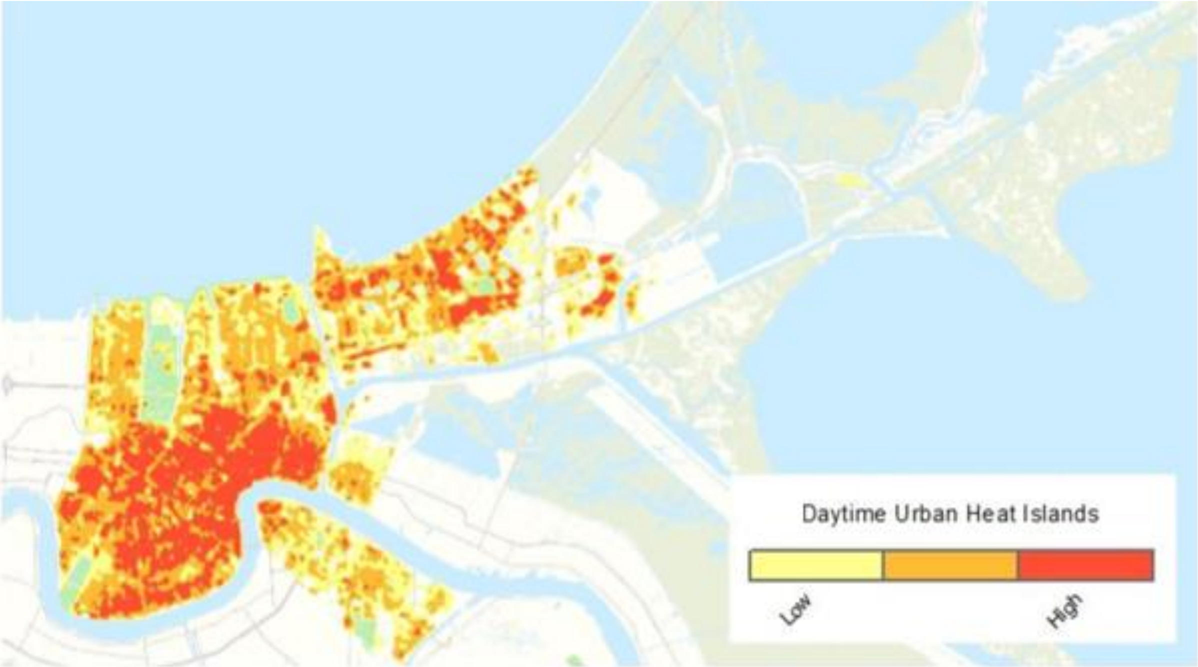
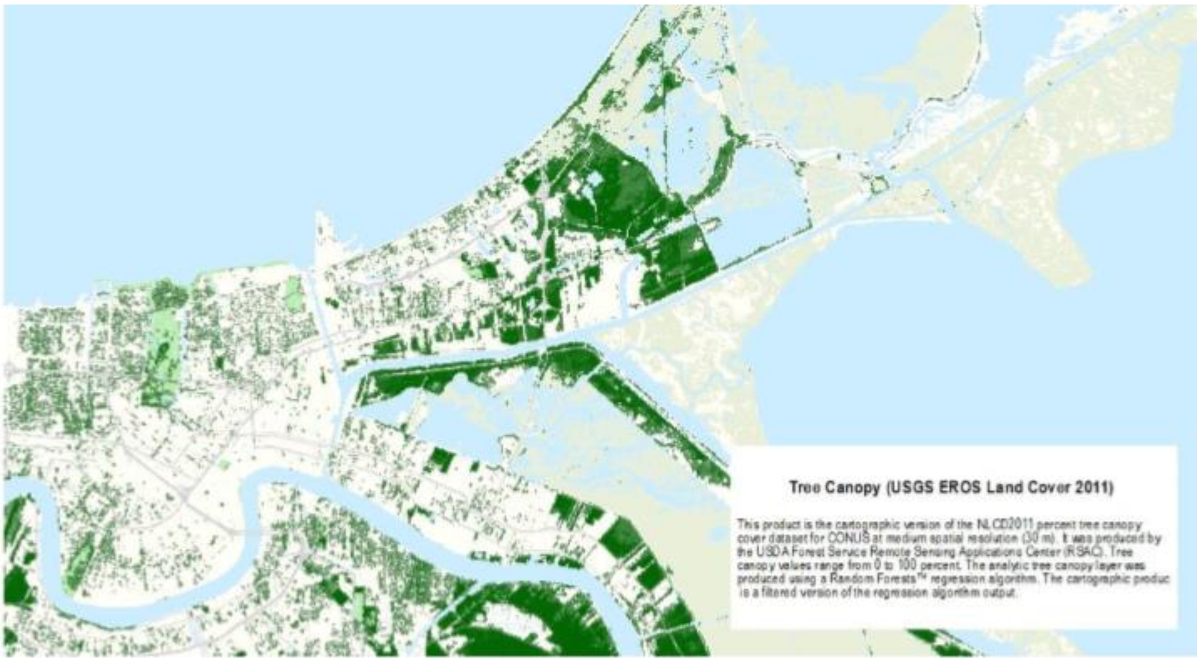


Figure 6.4.1: Map of elevated temperatures at least 1.25°F above mean daytime temperature. This analysis was completed by The Trust for Public Land based on LANDSTAT data. Source: (New Orleans Health Department, 2018)



Tree Canopy (USGS EROS Land Cover 2011)

This product is the cartographic version of the NLCD2011 percent tree canopy cover dataset for CONUS at medium spatial resolution (30 m). It was produced by the USDA Forest Service Remote Sensing Applications Center (RSAC). Tree canopy values range from 0 to 100 percent. The analytic tree canopy layer was produced using a Random Forests™ regression algorithm. The cartographic produc is a filtered version of the regression algorithm output.

Figure 6.4.2: Map of New Orleans Tree Canopy by USGS EROS Land Cover 201. Source: (New Orleans Health Department, 2018)

Furthermore, according to the Louisiana Health Department, 0.49 per 1000 of the black New Orleanians population and 0.23 per 1000 of the white residents was seeking care for heat related emergencies in the period from 2010 to 2012. In addition, more than 50% of the heat related 9-1-1 calls occurred between 11:00am and 3:00pm during days with high temperatures (Figure 6.4.3).

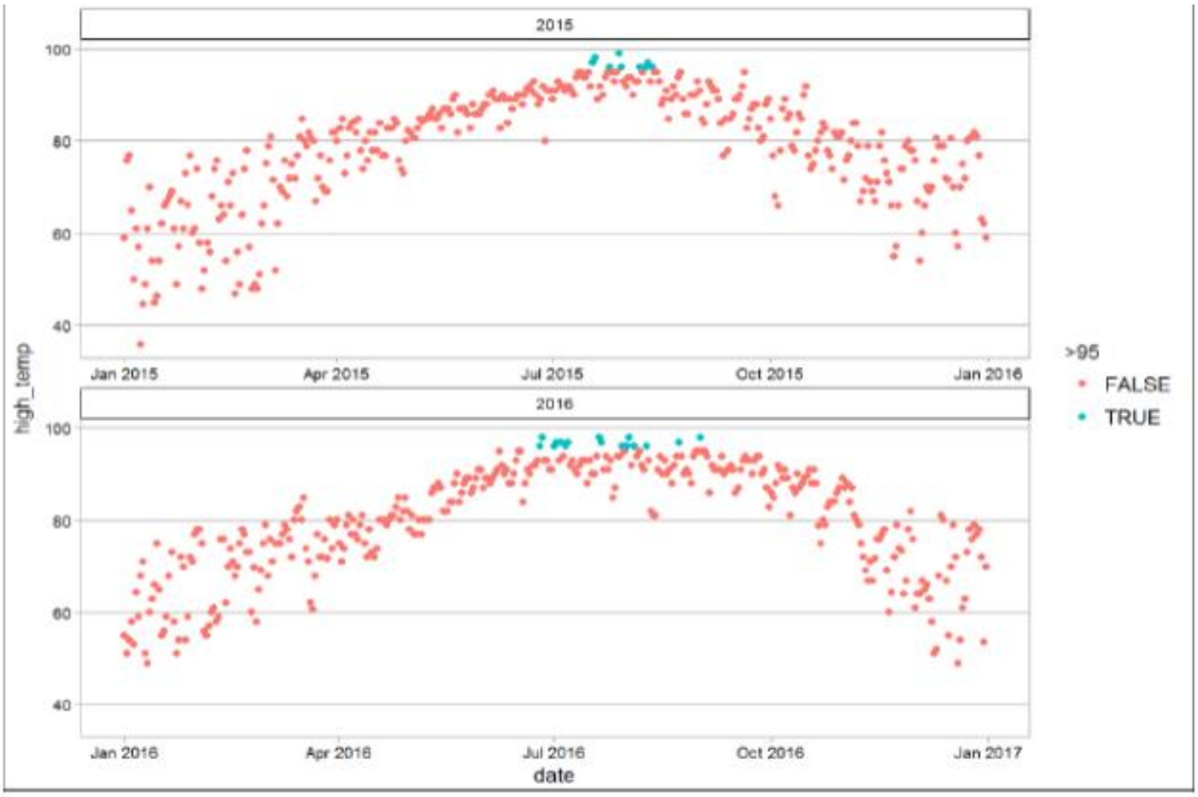


Figure 6.4.3: Recorded high daytime temperatures in 2015 and 2016. Blue dots are days when New Orleans Emergency Medical services received heat-related calls for service. (Source: New Orleans Health Department, 2018)

6.4.2 Mosquitos

In southeast Louisiana, mosquitoes are the most important transmitters of vector borne illnesses (New Orleans Health department, 2018). They thrive best in warm and humid environments. However, not all mosquitos are transmitting diseases. According to Lewis, mosquitos which are born in floodwater and brackish water are in general not dangerous to humans. Mosquitoes that do pose a health risk are born in fresh still standing water, especially water in little containers, flower pots and wheelbarrows are the prime breeding grounds of mosquitos after a rainstorm (figure 6.4.4). Land subsidence which causes dead water storage places increase the amount of potential breeding places too. The three most common mosquitoes in Orleans Parish and their transmission diseases are showed in table 6.4. The West Nile virus outbreak of 2002 in Louisiana shows the severity of the impacts. This outbreak caused 24 premature deaths, 204 hospitalizations, 135 emergency room visits, and 5,800 outpatient visits. The total health-related costs reached $207 million ($46,449 per 1,000 people; New Orleans Health department, 2018). The mosquito season will be enlarged when temperatures are rising. Because of this, the risk of vector-transmitted epidemics such as Zika and West Nile Virus will occur more often.

Figure 6.4.4: Potential mosquito breeding place (Bayou ST. John)

Table 6.4: Most common mosquitos in New Orleans and their possible transmittable illnesses. Source: (New Orleans Health department, 2018)

Type	dengue	yellow fever	West Nile viruses	Zika	St. Louis encephlitis	Chikungunya Virus
Aedes aegypti	x	x		x		
Aedes Albopictus	x	x	x	x		x
Culex Quinquefasciatus			x		x	

6.4.3 Drinking and surface water

New Orleans has two drink water treatment plants, the Carrollton Water Plant and the Algiers Water Purification Plant (Figure 6.4.5). These plants purify 54 billion gallons of river water per year and delivers drinking water to 354.000 people (Sewerage & Water Board of New Orleans). The intake pipe is about 153 km (95 miles) upstream where the Mississippi branches off before entering the Gulf of Mexico. Drought and heat impact the quality of the river water similar as in the Netherlands (5.4). In addition, river water is affected by pollution from treated sewage water from cities upstream and due to the many industries along the river (Buchanan, 2011). Another threat is the salt spike which intrudes from the ocean upstream. Furthermore, limitation of shipment caused high economical losses among others in 2012 during low river levels. In addition, the used steam pumps for water treatment needs more cooling water and more chloride is added to the water during heat waves. Besides, the discharge of hot water during summers may cause problems.

Figure 6.4.5: 1. Jefferson Parish Water Treatment Plant; 2. Carrollton water purification plant; 3. Carrollton water treatment plant; 4. Outflow treated water from Jefferson; 5. New River & Oak Street Intake Pump station; 6. Outflow treated water from Carrollton.

7. Mitigation options New Orleans

In New Orleans, drought occurs in a shorter time period than in the Netherlands. Moreover, most drought related damages are caused by two types of subsidence. The first is differential subsidence which is caused by decreasing groundwater levels as a result of the drainage of waste sewer and storm drainage pipes (figure 7.1). The second type is shrink and swell. This is cause by seasonal precipitation varieties (more or less rain) and is possibly enlarged due to the decrease of groundwater levels. This process is strongly soil type and clay type dependant. However, there is little known about how this process works. All measures which can be taken to mitigate drought and heat impacts are showed in annex Q. Furthermore, to identify the vulnerabilities of water nuisance, heat, drought and flooding all Dutch municipalities must have carried out a climate stress test by 2019 to make the Netherlands water-robust and climate-proof in 2050 (Annex R). Such a stress test is also interesting for New Orleans.

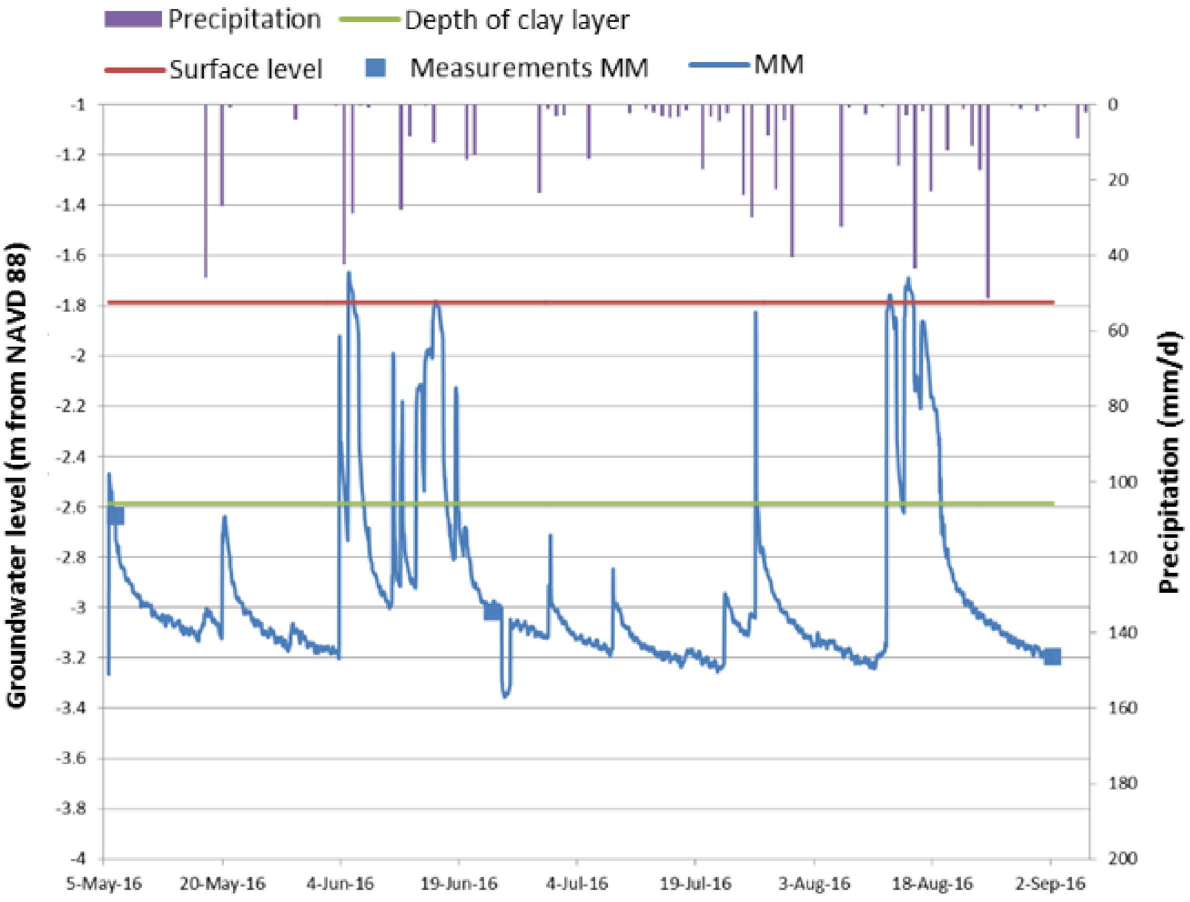


Figure 7.1: The variation of groundwater levels in New Orleans. Source: (Stuurman, 2019)

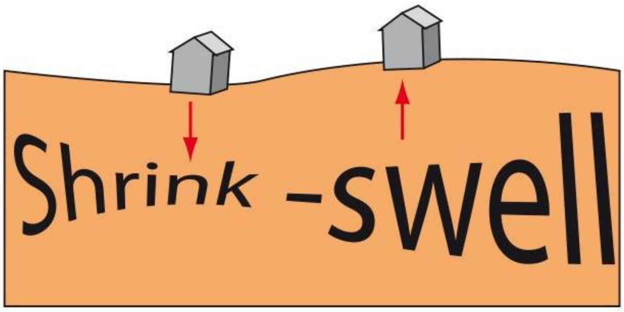


Figure 7.2: Schematic image of the process of shrink and swell. Source: (Stuurman, 2019)

7.1 Drought mitigation options

The first measure is monitoring and archiving all impacts. In addition, most damages can be limited when ground water levels are maintained at a stable level above the clay layers. This limits the process of shrink and swell. For New Orleans, this means that the use of the stormwater drainage pumps should be limited and that the underground infrastructure has to be repaired. Moreover, the storage of fresh water in wet periods is important. The Netherlands uses the IJselmeer as fresh water buffer. Maybe New Orleans is able to create such freshwater buffer as well. Additional advantages of a fresh water buffer is new potential drink water source and it can reduce the effect of seepage. Moreover, green & blue infrastructure can be implemented to store water to maintain the groundwater levels high. Like raingardens which enlarge water infiltration into the soils and may reduce the use of pumping stations. Furthermore, root barriers and root bunkers are used in the Netherlands to prevent damages to roads and pipelines by growing tree roots during drought. Moreover, water can be stored in tree bunkers to supply water in every period. In addition, during meteorological drought, the small-scale water construction facility (KWA) takes into action, which provides the West Netherlands with fresh water in dry periods and in prolonged periods of water shortage, Dutch water managers using ''the displacement series'' for the distribution of the available freshwater (Figure 7.3; *Ministerie van Infrastructuur en Waterstaat, 2019*).

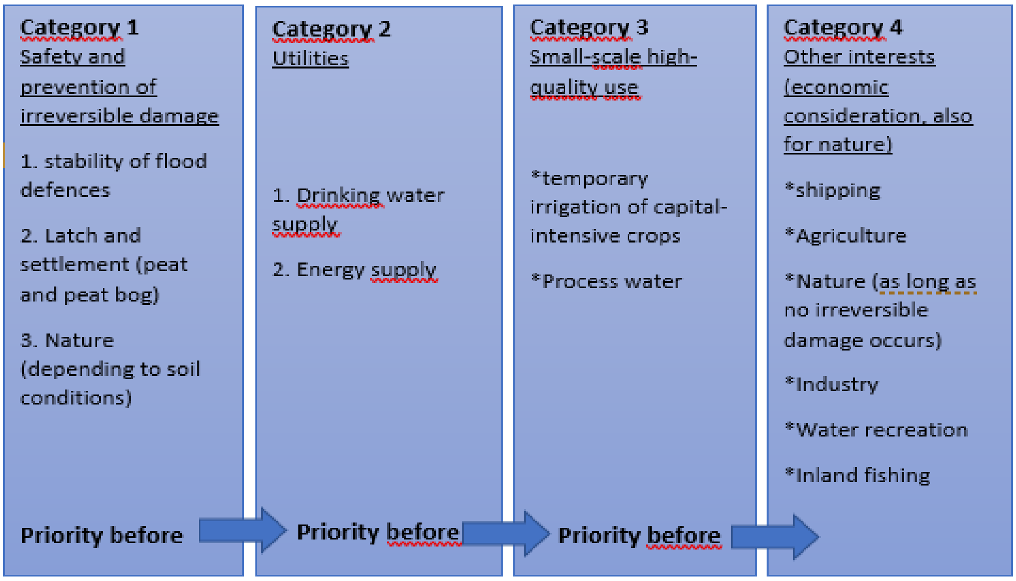


Figure 7.3: Displacement series. Source: (Ministerie van Infrastructuur en Waterstaat, 2019)

7.2 Heat mitigation options

Green infrastructure is one of the main measures to reduce the effects of extreme heat, because one tree has the same cooling effect as ten air conditionings due to evapotranspiration (Döp et al., 2011). Furthermore, new building projects must take extreme heat events into account to limit the impacts by using heat resistant materials with a high albedo, better insulation, orientation (optimal ventilation and shadow) or cooling due to evaporation by irrigating parking lots and parks. In addition, installing air-conditioning in houses is effective to limit heat stress. To keep the water quality in the city high, can be done by installing a sufficient water network to increase the opportunity for circulation and flushing possibilities by using river water and an additional water buffer. Furthermore, there should be additional supervision of permits from companies for the discharge of cooling water to maintain the quality of river water high. Besides, creating awareness by inform people about heat related risks is an important measure. Currently, warning systems and action plans during extreme heat are the ''National Heat Plan'' for in the Netherlands (RIVM, 2015) and in New Orleans it is called ''Heat advisory'' (City of New Orleans, 2019).

8. Discussion

8.1 Reliability 1000 years weather in the low lands

Information gaps are certain, over the years wars and fires have destroyed sources and it depend strongly what people wrote down (table 8.1). Therefore, the interpretation of the intensity of warm and dry periods is debatable. Nevertheless, literature from Buisman is reliable enough to obtain a broad overview about drought and heat from the past thousand years. Moreover, the first sources were from England, France and Germany. Therefore, it is difficult to determine which drought and heat impacts appeared in the Netherlands.

Table 8.1: Reliability of the sources

Years	Sources	Locations Netherlands	National overview (NL)
Before 1706	Descriptive	<ca.5	deficient
1706-1746	Descriptive / instrumental	Ca. 5 tot 25	deficient
Since 1747	Descriptive / instrumental	>ca.25	reasonable

8.2 Meteorological data of the past 100 years

8.2.1 Reliability of the meteorological data

In the Netherlands, long continuous meteorological and river discharge datasets are freely available since 1900. To indicate drought periods is much more difficult for New Orleans. Available PDSI values of Louisiana are available from 2000 to 2018 and PDSI values of the county Orleans are from 1975 to 2010. Nevertheless, the PDSI values at county level correspond with the values at the state's level (2000 and 2006) and thus I assume that the four used drought years are relatable with drought in New Orleans. Precipitation and temperature data are well accessible (1948-2019; New Orleans International airport). However, evaporation and solar radiation data which are useful to calculate precipitation deficits are only from the period 1961 to 1990. Therefore, characteristics of recent drought events are difficult to compare due to the incomplete data.

8.2.2 PDSI

The largest shortcoming of the PDSI value is that it is developed for identifying drought affecting agriculture. In the calculation it is assumed that runoff only appears at field capacity, but this is especially in urban areas not correct. Moreover, it is designed to identify drought on the long-term (several months) and does not identify rapidly emerging drought situations well.

8.2.3 Precipitation deficit

Originally, the precipitation deficit is developed for the agricultural sector. Furthermore, precipitation deficits are around 300 millimetres higher in New Orleans than in the Netherlands. An important difference in the calculation is the use of the crop reference evaporation in the Netherlands and pan evaporation in New Orleans. Figure 8.1 shows for New Orleans higher values of evaporation using the pan evaporation method. Furthermore, whether the evaporation data is applicable in urban areas is debatable due to the high rate of paved surfaces. Rainwater is drained fast to the drainage systems, whereby less water can infiltrate into the soil and there is less time to evaporate. Nevertheless, precipitation deficits in New Orleans are significantly higher than in the Netherlands but there is no literature that New Orleans experienced drought problems in 1976 and 1990. Therefore, the experience of high precipitation deficits is different between the Netherlands and New Orleans. This is due to lower soil water availability in the Netherlands, resulting in less water which can be evaporate. Moreover, 55% of the drink water pipes in New Orleans are leaking which supplies 1 millimetres water per day into the soils. Another possible variable is the water availability through the influx of seepage. In addition, the Dutch method is not completely right for New Orleans because the growing season in New Orleans is longer (220 to 320 days; Howard & Norrell, 2019).

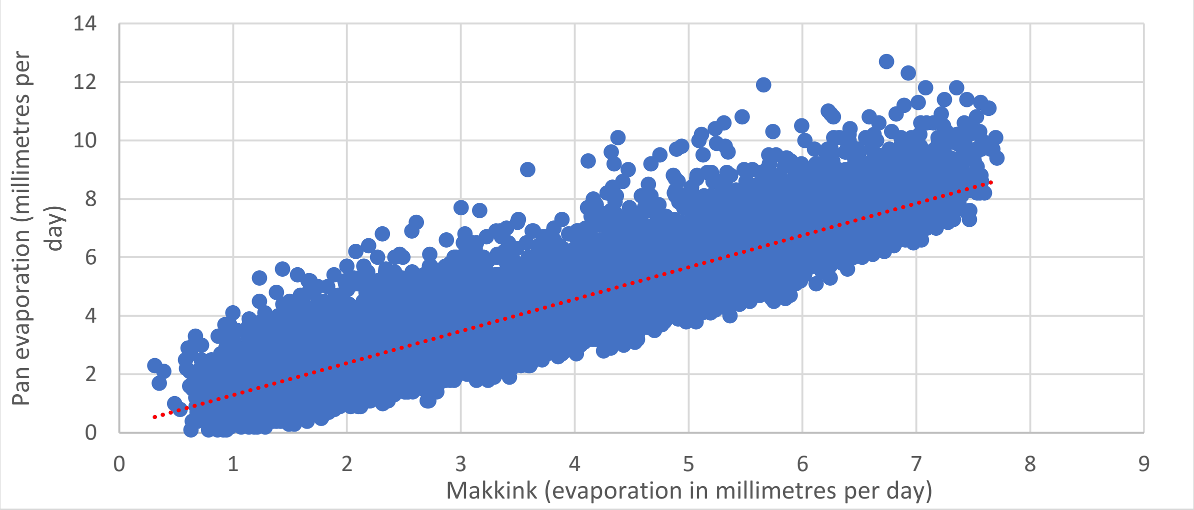


Figure 8.1: Makkink method vs Pan evaporation in New Orleans (1961-1990)

8.2.4 Heatwaves

The experienced heatwaves days during a year are almost not comparable (Figure 8.2). The people in New Orleans are more used to extreme heat. Therefore, they experience the impacts of a heatwave differently.

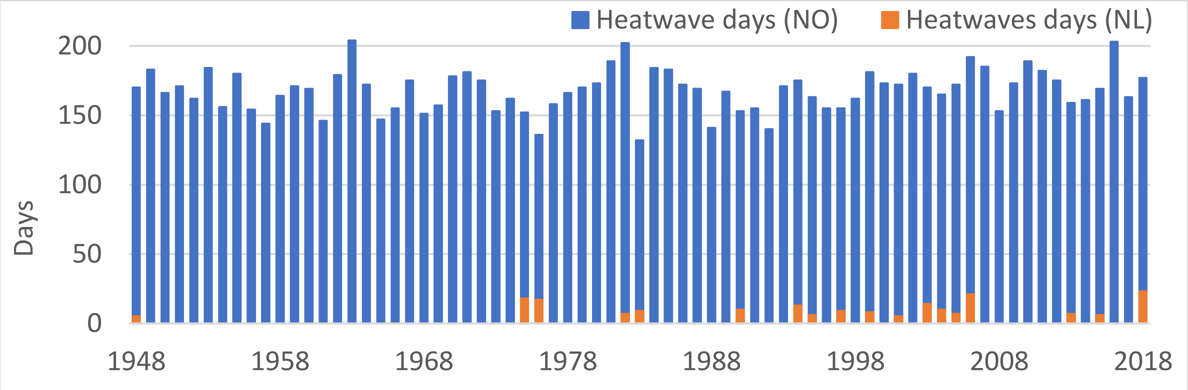


Figure 8.2: Cumulated number of heatwave days within a year (All days cumulated that satisfy 5 consecutive days or more above 25 °C of which at least 3 are above 30°C) in The Netherlands and New Orleans.

8.3 Rhine and Mississippi discharges in correlation with drought

Rhine discharge data in combination with drought are reliable because of the long continuous data sets. Discharge data of the Mississippi is more debatable, because the used data is from Tarbert Landing (1930-2019) which is further upstream (Figure 4.2). However, there are no major arrivals or branches of the Mississippi downstream which make discharge values useful for New Orleans. In addition, the correlation of drought and discharge between the Mississippi and the Rhine is different due to the size and the location of the catchment area, and the precipitation patterns (figure 8.3). First, the catchment of the Rhine (185000km2) is significant smaller than the Mississippi (3.2 million km2). In addition, the dominant wind direction of the precipitation supply into the Rhine catchment is from Northwest which is parallel to the flow direction of the Rhine.

Moreover, potential precipitation from the south is blocked by the Alps and wind directions from East/Northeast brings warm dry weather. So, when there is a drought in the Netherlands, it is reasonable to assume that it is dry in the entire catchment resulting in lower river discharges. For the Mississippi dominant wet wind directions are from the west. Furthermore, rainstorms are coming from the south and the Rocky Mountains don't block wind from the north. While, the Mississippi flows from North to South, the chance is higher that it rains somewhere in the catchment area.

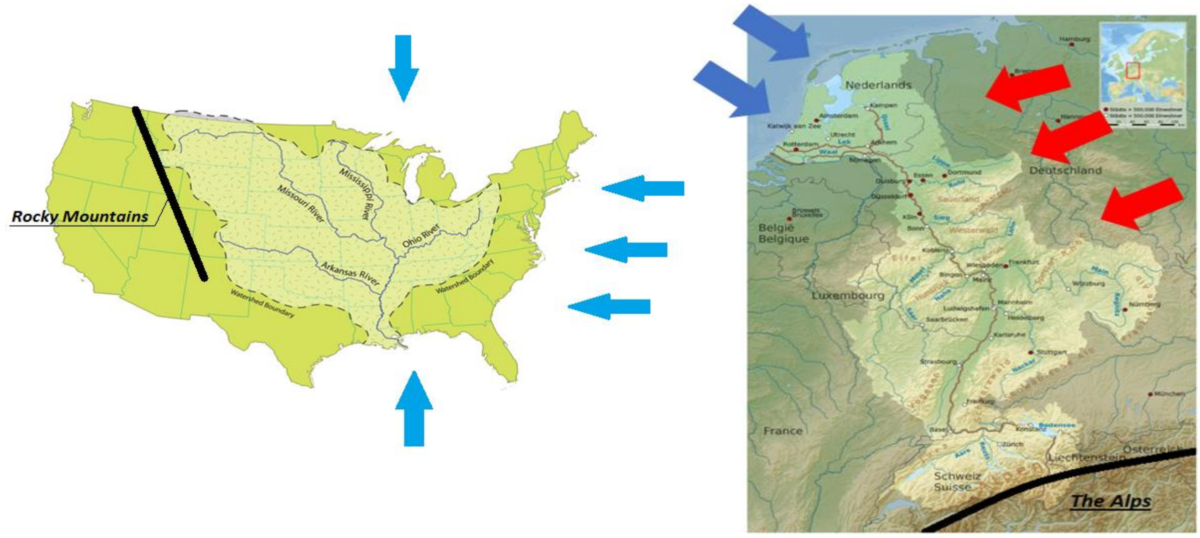


Figure 8.3: Mississippi catchment dominant wind directions (Left) and Rhine catchment with dominant wind directions (left). Blue arrows are precipitation directions. Red arrows are dry warm weather directions.

8.4 Urban drought definition

Currently, drought definitions (precipitation deficit and PDSI) are based on agriculture. In order to obtain a good overview of how drought manifest in urban areas, a new definition must be implemented to define urban drought. One used definition is drink water availability. However, low groundwater levels have major impacts in cities too and is dependent on many different parameters. Table 8.2 shows the requirements which should be taken into account how soil dehydration is caused in cities.

Table 8.2: Processes which affect the groundwater levels

Inflow	Depending on	Outflows	Depending on
Precipitation	Amount and intensity	**Precipitation**	Percent of the area which is impermeable
	Percent of the area which infiltrates rainwater	**Groundwater**	Drainage by storm drainage pipes
Other water soil recharge sources	Broken drinking water pipes	**Groundwater**	Drainage by broken sewage systems
	Seepage	**Groundwater**	Private and public groundwater abstraction
Storage	Soil moisture capacity	**Groundwater**	Soil permeability and holding capacity
	Amount of inlet water from lakes and rivers into the city system	**Evaporation**	Temperature
			Humidity
			Amount/ type of vegetation

8.5 Method Impacts

The used method to analyze drought and heat impacts in the Netherlands is sufficient to obtain a clear overview. However, it is possible that some damages, like at the main road network, will remain hidden because the culture is often to resolve damages instead of doing research and archiving this. Drought-related damage can also remain hidden because it only appears several months (in the winter) or even years later (Stuurman, 2018). In New Orleans, the overview of drought impacts is not complete. There is not much literature written about drought impacts and during the interviews, it became clear that drought does not play a major role in society. Extreme heat impacts were also hidden in New Orleans because they are more used to extreme heat than in the Netherlands.

8.6 Mitigation option

Drought

Repairing underground infrastructure may have unforeseen consequences on the groundwater table. Water levels may decrease when drinking water pipes will be repaired. On the other hand, repairing and restructure sewage and draining systems could result in higher groundwater levels. Furthermore, maintain high groundwater levels should not increase the risk of flooding during extreme precipitation in New Orleans. As example, in the Netherlands, drought lead sometimes unexpectedly to waterlogging because water boards try to keep the surface water level as high as possible during drought periods to prevent land subsidence. Adjacent areas that subsided in the preceding period can then suffer from flooding. A good monitoring system must be established that monitors the vulnerable areas in New Orleans so that the risk of this type of flooding is excluded. In addition, raingardens should be introduced at a larger scale but, more research is needed to understand how much impact raingardens have on groundwater levels and how they perform during a drought. Vegetation grows very fast due to the warm and humid climate in New Orleans which probably compensates the drought impact on vegetation.

Heat

Using air conditioning to counteract heat stress has some drawbacks. Air conditioning releases chlorofluorocarbons and hydro-chlorofluorocarbons which is part of the greenhouse gases that trap heat and lead to depletion of the ozone layer (Wessels, 2016). Besides, continuously using air conditioning causes health risk, because the air filters lose a bit of their integrity and allow passage of harmful compounds from outside into your home or office. These can trigger allergies and, in some cases, even cause eye, nose and throat irritation. Moreover, the increasing use of air conditioning during heat periods increases the demand of electricity which lead to more electricity production and CO2 emissions. Furthermore, an air conditioning does not cool effectively at extremely high humidity levels (Sternad). As a result, the costs and electricity use are even higher. The electricity network is therefore more burdened and the risk of loss of electrical power increases which could jeopardizing the health of those who depend on electricity for their medical needs. In addition, green infrastructure, also requires further research. Questions should be asked how trees affect the groundwater levels. Do they extract more water resulting in more damage to roads and houses and creates rooting more soil permeability?

9. Conclusions

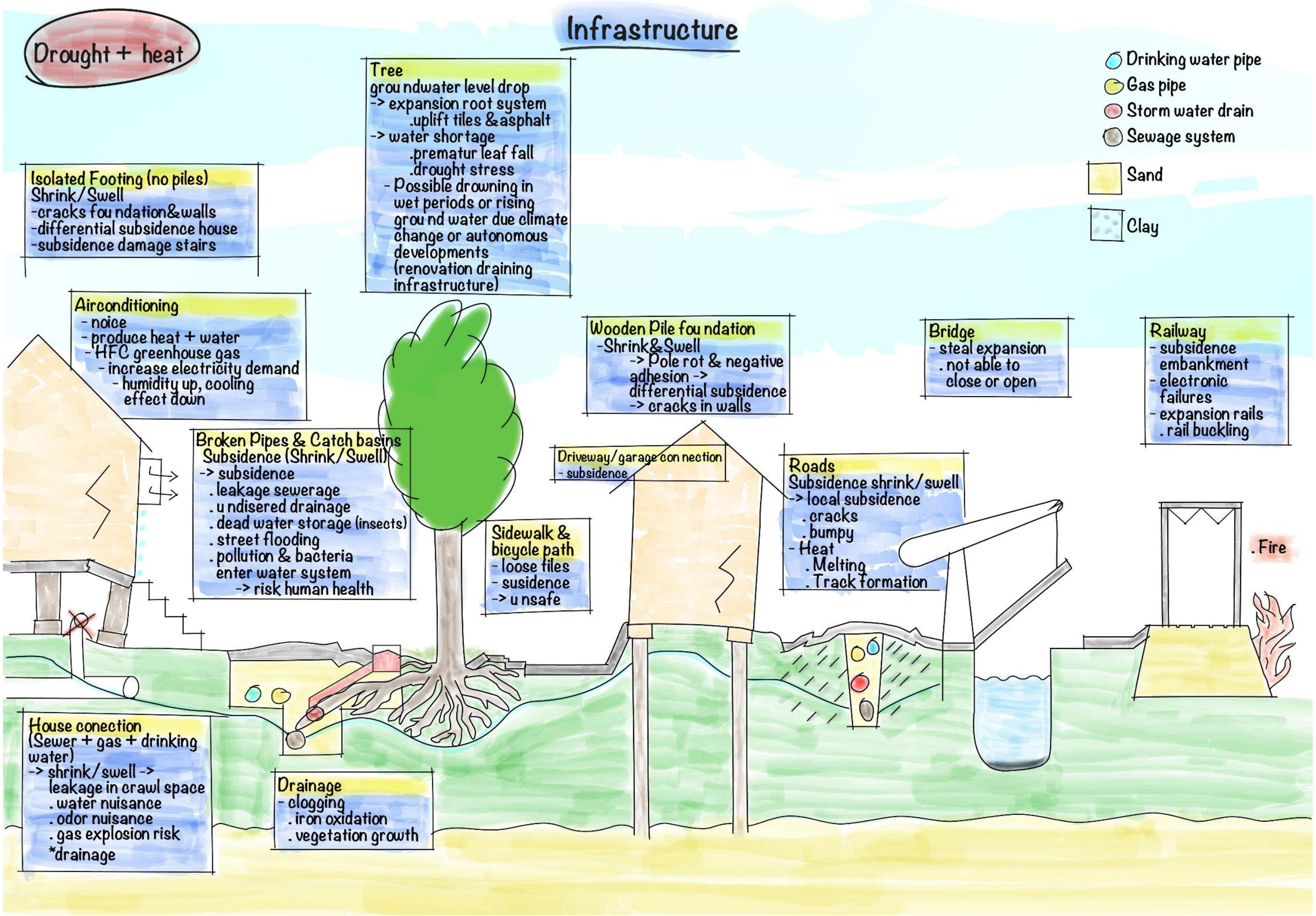
Results of this thesis show the differences and similarities of the occurrence, the socio-economic impacts and the adaptation strategies of severe drought and extreme heat events in the Netherlands and in New Orleans. At first, the meteorological and hydrological characteristics of drought and heat events are different between the two study areas. In New Orleans, long term meteorological drought occurs rarely and is often interrupted by intense rain showers. In addition, temperatures are always high during the summer. In the Netherlands meteorological drought can appear for several consecutive months whereby the temperatures are often above average. However, the number and duration of heatwaves are much higher in New Orleans. In a historical context, drought and heat were not always compound events. Nevertheless, during the medieval warm period, drought was often accompanied by great heat but in the small ice age, drought appeared often without extreme heat. In the past 100 years, drought and heat periods were often compounded again. Moreover, it is expected that drought and heat will appear more often in New Orleans and in the Netherlands due to the expected temperature rise of 2-3°C during this century. Furthermore, drought periods may occur faster due to increasing evaporation rates. Therefore, drought and heat will become more often compounded. In addition, there is a correlation between meteorological drought periods in the Netherlands and low Rhine discharges. For New Orleans, this correlation is not that clear, making it more unpredictable whether there is a meteorological drought at the same time as hydrological drought in the lower Mississippi area.

Nevertheless, both areas experience similar socio-economic impacts caused by severe drought and heat (summarized in the drawings below). Drought impacts includes damages to infrastructure, greenery and housing. Furthermore, drought enhance salinization, subsidence, and it limits river navigation. Resulting all in high economical losses and repairing costs. In addition, these impacts are causing dangerous situations on roads and endangers the fresh water availability which poses a risk for human health. Heat related impacts causes infrastructural damages and leads to increasing energy demands. Moreover, extreme heat affects human health and even resulting in higher death rates. In addition, the water quality declines and the increase of vector borne diseases are important issues. Even though drought and heat related impacts are similar in the Netherlands and in New Orleans, the occurrence of damages is different between both areas. This because in the Netherlands, the main cause of drought impacts is due to long term meteorological drought in combination with hydrological drought. In New Orleans, drought related impacts are mainly caused due to the large varying groundwater levels which is partly human induced resulting in differential subsidence and shrink and swell. In addition, the cause of heat related consequences is in both areas the same and are strengthened due to the urban heat island effect.

The most important measures to reduce the negative effects of drought is maintaining the groundwater levels at a high elevation. This can be achieved by storing freshwater during wet periods and using river water and freshwater buffers during meteorological drought and by creating a water network in the city to get more control over the entire water system. This measure does not only reduce the impacts of drought but also reduces further land subsidence and additionally the effect of seepage by rising sea levels. To reduce the heat island effect, green and blue infrastructure should be integrated in the city planning. Besides architects should keep the impact of heat in mind during the design of buildings. Furthermore, to remain the water quality of a sufficient level during heat events, can be done by installing a well-connected water system for flushing possibilities. Furthermore, searching for alternative fresh water resources is needed to be more sustainable with available fresh water. In addition, provide people with accurate information and a proper education about the direct risk of heat and the indirect effects as the increase of vector borne diseases in a becoming warmer environment is needed.

Infrastructure

Drought + heat



Isolated Footing (no piles)
Shrink/Swell
-cracks foundation&walls
-differential subsidence house
-subsidence damage stairs

Tree
groundwater level drop
-> expansion root system
.uplift tiles &asphalt
-> water shortage
.prematur leaf fall
.drought stress
- Possible drowning in wet periods or rising ground water due climate change or autonomous developments (renovation draining infrastructure)

Airconditioning
- noice
- produce heat + water
- HFC greenhouse gas
- increase electricity demand
- humidity up, cooling effect down

Wooden Pile foundation
-Shrink&Swell
-> Pole rot & negative adhesion ->
differential subsidence
-> cracks in walls

Bridge
- steal expansion
. not able to close or open

Railway
- subsidence embankment
- electronic failures
- expansion rails
. rail buckling

Broken Pipes & Catch basins
Subsidence (Shrink/Swell)
-> subsidence
. leakage sewerage
. undisered drainage
. dead water storage (insects)
. street flooding
. pollution & bacteria enter water system
-> risk human health

Driveway/garage connection
- subsidence

Sidewalk & bicycle path
- loose tiles
- susidence
-> unsafe

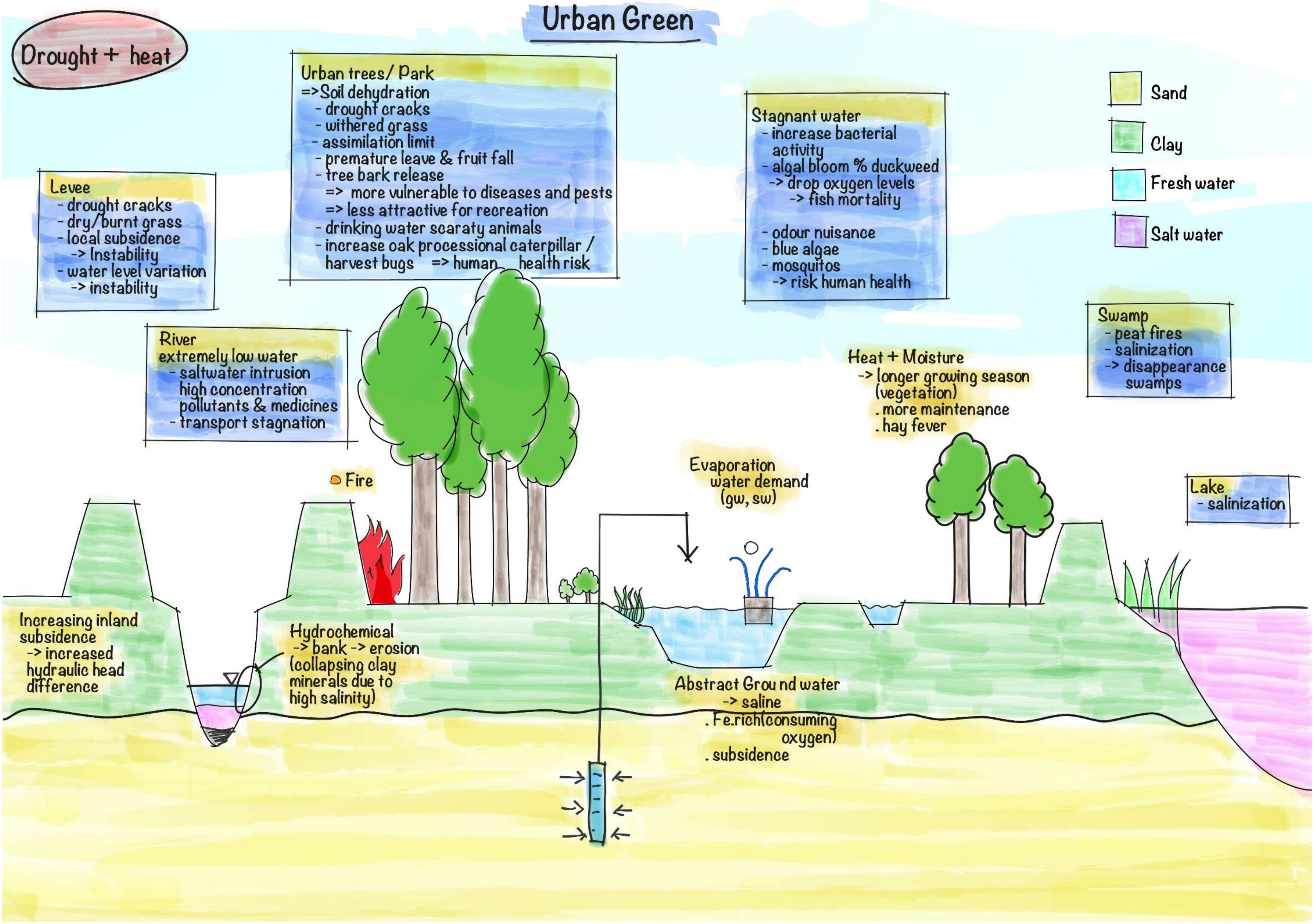
Roads
Subsidence shrink/swell
-> local subsidence
. cracks
. bumpy
- Heat
. Melting
. Track formation

. Fire

House conection
(Sewer + gas + drinking water)
-> shrink/swell ->
leakage in crawl space
. water nuisance
. odor nuisance
. gas explosion risk
*drainage

Drainage
- clogging
. iron oxidation
. vegetation growth

Urban Green



Drought + heat

Levee
- drought cracks
- dry/burnt grass
- local subsidence
  -> Instability
- water level variation
  -> instability

Urban trees/ Park
=>Soil dehydration
- drought cracks
- withered grass
- assimilation limit
- premature leave & fruit fall
- tree bark release
  => more vulnerable to diseases and pests
  => less attractive for recreation
- drinking water scaraty animals
- increase oak processional caterpillar / harvest bugs => human health risk

Stagnant water
- increase bacterial activity
- algal bloom % duckweed
  -> drop oxygen levels
    -> fish mortality
- odour nuisance
- blue algae
- mosquitos
  -> risk human health

River
extremely low water
- saltwater intrusion
  high concentration
  pollutants & medicines
- transport stagnation

Swamp
- peat fires
- salinization
-> disappearance swamps

Heat + Moisture
-> longer growing season (vegetation)
. more maintenance
. hay fever

Fire

Evaporation
water demand
(gw, sw)

Lake
- salinization

Increasing inland subsidence
-> increased hydraulic head difference

Hydrochemical
-> bank -> erosion
(collapsing clay minerals due to high salinity)

Abstract Ground water
-> saline
. Fe.rich(consuming oxygen)
. subsidence

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Annexes

Annexes	Description
A	Outline PDSI tool calculation
B	Interviewed people in New Orleans
C	Color diagram, climate of the past 1000 years
D	Average temperatures per month in New Orleans
E	Dew point temperature New Orleans
F	Average precipitation per month New Orleans
G	Drought and heat occurrence/ impacts of the past 1000 years
H	PDSI values the Netherlands
I	Heatwaves in the Netherlands since 190111111
J	PDSI/Rhine discharge deficit (August to November)
K	SPEI/Rhine discharge deficit (August to November)
L	PDSI drought years in New Orleans
M	New Orleans tables temperatures and precipitation of the drought years
N	Heatwaves in New Orleans between 1948-2018
O	Effects of climate scenarios (2050) at drinking water intake points in the Netherlands
P	Walking tour ‘’Plant ecology tour’’
Q	Drought and heat mitigation options Infrastructure (Table 10-12), foundations (Table 13), Levees (Table 14), Nature (Table 15-20) and Human health (Table 21)
R	Stress test (the Netherlands)

ANNEX A

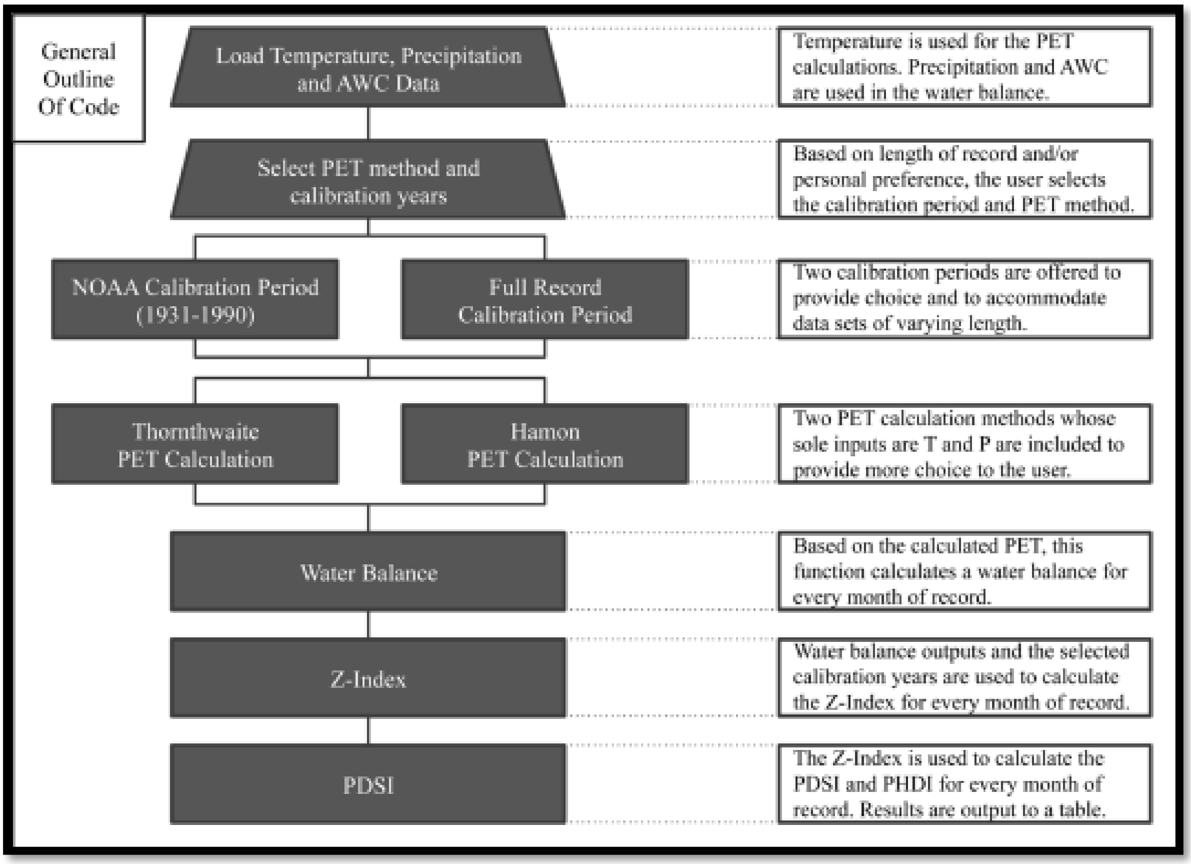


Figure 1: General outline of the tool to calculate the PDSI index. Where PET = potential evapotranspiration & AWC = Available water capacity. Source: (Jacobi et al., 2013)

Annex B

Table 1: People who are interviewed during the fieldtrip in New Orleans

Name	Company	Function	Date
Todd D. Reynolds	Groundwork	Executive Director	28-3-2019
Ramiro Diaz	Waggonner & Ball Architects	Architect	28-3-2019
Tyler Antrup	City planning department	City officer urban planner + resilience	29-3-2019
Aron Chang	Blue House (formerly: Waggonner & Ball Architect)	Community group leader (formerly: architect)	29-3-2019
Maggie Hermann	Blue House	Community worker	29-3-2019
Thorbjörn Törnqvist	Tulane University	Vokes Geology Professor in the Department of Earth and Environmental Sciences	31-3-2019
Sarah Olivier	New Orleans City Park	Director of Planning	1-4-2019
Edwin Welles	Deltares USA	Hydrologist/ Director	1-4-2019
John Taylor	-	Local resident	2-4-2019
Andy Sternad	Waggonner & Ball Architects	Architect	3-4-2019
Julia Kumari Drapkin	Iseechange	CEO	4-4-2019
David Waggonner	Waggonner & Ball Architects	Architect, CEO	4-4-2019
Dana Brown	Dana Brown & Associates	Landscape architect	5-4-2019
Delaney McGuinness	Dana Brown & Associates	Junior landscape architect	5-4-2019
Joshua Lewis	Tulane Universtiy; ByWater Institute	Research Assistant Professor, ecologist	5-4-2019
Thom Smith	LEED Green Assoc	Architect / Urban Designer	???
Abigail Phillips	Asakura Robinson	Project manager/ Landscape architect	30-3-2019

Annex C

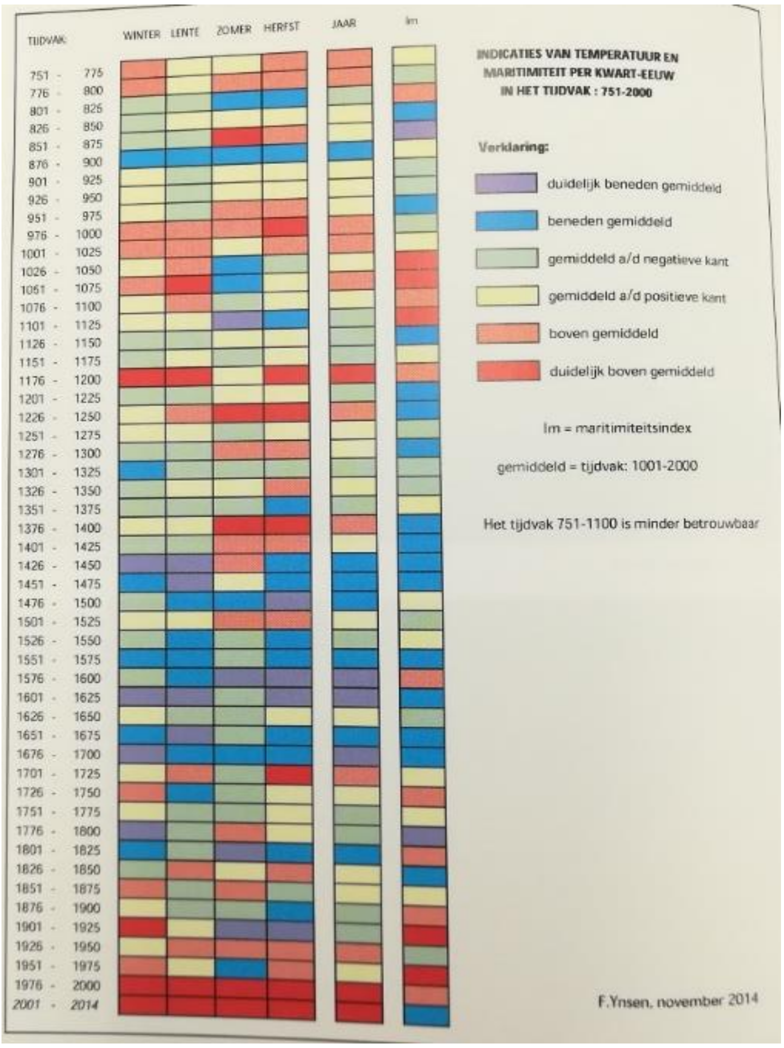


Figure 2: ***Indication of winter, - summer, spring and autumn temperature and annual temperature per 25 years in The Lowlands from 751-2014, purple is clearly below average and red is clearly above average. source: (Buisman & Engelen, 1995).***

Annex D

Table 2: Average temperatures per month in New Orleans (1971-2000). Source: (rssWeahter, 2015)

Month	Low (°C)	Low (°F)	High (°C)	High (°F)
January	6.3	43.4	16.6	61.8
February	7.8	46.1	18.5	65.3
March	11.5	52.7	22.3	72.1
April	14.7	58.4	25.6	78.0
May	19.1	66.4	29.3	84.8
June	22.2	72.0	31.9	89.4
July	23.4	74.2	32.8	91.1
August	23.3	73.9	32.8	91.0
September	21.4	70.6	30.6	87.1
October	15.7	60.2	26.5	79.7
November	11.0	51.8	21.7	71.0
December	7.5	45.6	18.1	64.5

Annex E

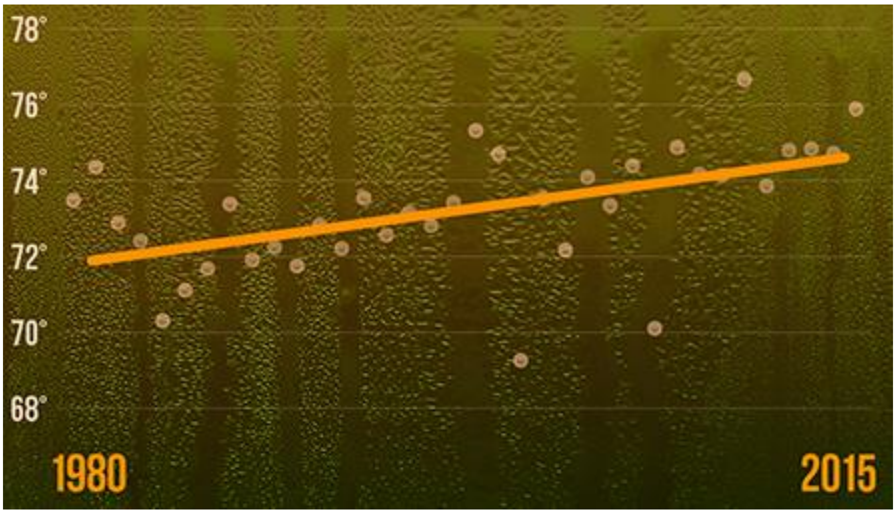


Figure 3: Dew point temperature New Orleans (Source: Climate Central, 2016b)

Annex F

Table 3: Average Precipitation amounts in New Orleans per month (1971-2000). Source: (rssWeahter, 2015)

Month	Millimetres	Inch
January	149.1	5.87
February	138.9	5.47
March	133.1	5.24
April	127.5	5.02
May	117.3	4.62
June	173.5	6.83
July	157.5	6.20
August	156.2	6.15
September	140.0	5.55
October	77.5	3.05
November	129.3	5.09
December	128.8	5.07
Total	1628,7	64,16

Annex G

Table 4 drought and heat occurrence/ impacts from the past 1000 years. Dryness index from 1 to 3 and warmth index from 1 to 9.

Book / Period	Warm	Dry	Impacts	where
Book 1/ PRE MAO				
793	(7/8/9)	Large drought	-Famine	England
838	(7/8/9)		-Dehydrated/ burnt soils	England
870	(7/8/9)		-People died due to heat stress during harvesting	Worms
872	(7/8/9)	1	-Fruits harvest failed	Quedlinburg
873	-		-Harvest failed -Locust plague	Area of the Franken
874	(7/8/9)		-Famines -Illness 1/3 of population died	Gallia and Germany 1
971		drought (July-September)	-City fires	
981	-	Exceptionally dry + warm	-	
988	8/9(+)	dry	-Field fruit harvest failed =>Many people died (famine)	Gembloers Germany 5 juli tot 13 augustus
989		Dry spring	-Famine	England
993	(7/8/9)	-	-Fruit harvest failed	
994	-	Exceptionally dry 3	-River levels very low - large fish mortality - Fruits and flax harvest failed - famines - people, pigs, cattle and sheep became ill (the black Plague) - Grasslands and trees totally withered - city fires	St jan
1078	7/8/9	Extremely dry + warm 3	-cattle died - grasslands totally withered -city fires -famines	Te Sens Bourgondie (+) Engeland
1095	7/8/9	2	- earth seriously dehydrated -crop failures -famine	England

1112	-	1		
1123	-	1		Kamerijk, ROda, Lincoln (England)
1128	7/8/9	1		
1130	7/8/9	1	-Rhine very low	Koln
	4/5/6	2	-water sources dried out -ponds and lakes dried out -Harvest failed	Normandie Gembloers bij Namen
Book 2/MAO (1170-1430)				
1137			- Rivers, wells and water sources dried out. -trees and wood withered / fires	
1157			-Thames dried out	England
1170	8/9	2		Middle- and west Europe
1185	7/8/9	-	-Air pollution	
1188	8/9	1	-Rivers, wells and water sources dried out.	
1198			-Moezel extremely low	Germany
1205	7/8/9	1		
1221	6	Very dry		
1232		-	-Swamps dried out	North-Netherlands
1236	8/9 4 months extrely hot	3	-Lakes and swamps dried out -Water mills out of operations - Earth showed many gaps and cracks - (Koren) Crops hardly grew -excellent grain harvest - city fires	S-England Brussel en Aken
1241	8/9	3	-Many rivers, lakes, swamps dried out -Windmills out of operation Parks are withered -Fields of grass dried out -Cattle died -Wine good rijngebied en Parijs -grain harvest failed	te rouen

			- Rederlijke graanoogst en fruit	St albans
1252	8/9	3Extreme drought and warm in spring and summer. Wind direction NO, N, O	- Earth seriously dehydrated - Many people become chronically ill or get a fever. - rivers dried out - withered trees and grasslands - apple, nuts, grain, wine harvest failed -Birds let their wings hang, open their beaks and stop singing. - Flies, fleas and other insects are a scourge -River shannon dried out	England -Paris and Metz
1253	-	3	-City fires -Premature fruit fall -Earth dehydrated -No river or sea fish at the market.	
1272			-Harvest failed due to drought -Famines -Black plague (Cattle) -illnesses	Denmark, Slavie,Schotland, England & France, Groningen
1276	-	2		
1277	-	2		
1284			-Fruits are ripe early -People died due to heat stress during harvesting -Harvest failed -city fires (Even ships and houses made of brick)	England Zutphen, Hamburg
1288	8/9		-Air pollution	England, London
1296	-	2	-Harvest failed	Hoei
1297	-	2		
Book 2				
1303	6	2 Drought period 8 months (1303) Warm and dry summer	-Water sources dried out -Rhine water level very low -Heat influenced the people	Colmar Europe

			-No hay for the animals -Many cattle died	
1304	7	2	-Wells dried out (in Mainze) -Rhine extremely low	Sunny west and middle Europe
1305	7	2	-Heatstress people -no hay for the animals -Cattle died	Near Paris London
1325	9	2 (4 months drought and heat in Paris)	- All water sources, swamps, dried out. -Farmers had to walk a mile or more with herds for a well -High fish mortality - shipping comes to a standstill -Thames very salty during a whole year	Egmond England
1326	9	2	-rivers, small stream, water sources and swamps dried out -Fish mortality -limited river navigation - Thames full year salt	
1331	8	2		
1333	8	2		
1340	4	3		
1351			-Rhine very low	Koln
1352	7	2	-Harvest failed due to heat (Koren)	
1361	8	2		
1375		2		
1383	8	2	-Water sources (wells) and streams dried out -Wine and grain harvest good	
1384	7	2Some places you can drive through the Rhine	-Water level Rhine very low -Wells and streams dried out -Cattle died lack of drinking water -Crop failures	Westminster France
1385	8	2		

1390	8	2		
1393	8	2	- Water level Rhine very low - Wells and streams dried out - Earth dehydrated - Caterpillar plague	West- and Middle-Europe
1400	8	1		
1420	9	3	- Most rivers and streams a dried out - Earth surface dehydrated - Withering of leaves, trees and grass - City fires - Good grain and fruit harvest - Famine (severe winter, dry spring)	Europe
1422	9	3	-Wells dried out -More children got the smallpox due to extreme heat. Also adults. Especially children became seriously ill and either died or remained blind. -Good grain, whine and fruit harvest	
1424	8	3		
1442	9	2		
1447	8	2		
Book 3				
1458	6	2 Drought form March until Oktober	- Black Plague - City fires - Good and early whine year	
1459			-Water levels low (De Bekel)	
1471	8	2	-Early harvest -Ponds dried out -Water shortage animals -City fires -Salinization waters	
1473	9	2 Extremely warm in March, April and May	-City fires -wild fires (forest, moorland and peat)	

			-River water levels very low -Air pollution (air thick, some places the sun can not pass through) -People suffer from dysentery, heart attack or heatstroke -water stinks -whirlwinds arise	
1492		2	-Water mills almost fully out of operation -Water shortage -The sun burns the earth to ashes -City fires	
1494		2	-Low water (de Berkel) -Wells dried out	
1498	6	2		
1503	7	2	-Vegetation dehydrated -Forest, moreland fires City fires	
1504	8	2	-Harvest withered (Rijnland) -Locusts plague -City fires -Whine early and good quality	
1513	6	2	-Ponds dried out -Rhine is low	
1517		Dry?? winter	-City fires -Forest fires: Vosges. -Seine and other rivers very low -May, water is more expensive than wine -Withering of crops -Shipping is hampered.	!! Maizieres, Twente Vosges
1524	6	2	-Canals dried out, Water shortage Korn and fruit harvest failed -City fires	Zwolle
1540	9	3 Summer extremely warm. Central and Western Europe Mediterranean	-Mouse plague -Rhine water level extremely low -Fish ponds, ditches and canals dried out	Middle and west Europe

		temperatures for months, Water shortages until end of November.	-moorland, forest fires -village and city fires -withering of trees, grass and bushes - water mills can hardly turn - harvesting record early	
1545	4	2	-Cattle died due to shortage water -City fires	
1554	7	3	-City fires	Goes
1556	9	3	-Small streams and swamps dried out -Grass, trees withered -Koren, fruit withered -Many fires -Water quality decrease bad smell canals	Den Bosch Groningen
1567	7	3	-Cattle died due to water shortage -Black plaque, Pokken, buikloop, hoest -Large forest fires	Hoorn delft Leiden
Book 4				
1578	7		-Meuse and Seine very low -Black plaque -Harvest fruit, grain and whine abundant	West en midden europa
1580	6		-many illness -Rhine very low	
1590	7	2	-Forest, moorland fires -Village fires -Water shortage (animals) -Lek very low	
1601	4	3		
1604	6	3	-water levels very low -extreme water shortage -vegetation withered -city fires	Frankrijk wel droog Engeland Zierikzee Luik Wesel Essen
1612	5	3		
1616	7	3		
1619	5	3	-Grass shortage (no food animals)	

			-ditches dried out	
1634	5	2		
1636	7	2		
1669	7	3	-many illness -water levels very low and smells bad -saltwater intrusion -Rhine very low	
1670	5	3		
Book 5				
1676	7	2	-Wells dried out -Water mills out of operation	
1681	6	2		
1684	8	2	Warm and dry until June - September no wind, so mills cannot grind, bakers cannot make bread. - far too little grass and very low water ditches - lots of forest and heather fires	- de Zaan -Beemster, Schagen
1691	7	2	-Water mills out of operation -Water wells dried out	
1702	5	1		
1719		2	-rivers and ponds dried out -fish mortality	The Netherlands Arnhem
1723	5	1		
1731		1		
1732		1		
1733		1		
1741??	4	3	-People dazed along the way -Bridges torn -Bricked rain buckets broke	The Netherlands
1742	4	3		
1743	4	3		
1744	3	3		
1747	5	3	Water shortages	
1748	5	3		
1749	5	3		
1750	6	3	People, animals and fish died	Zaandam Amsterdam
Book 6				

1757	-	1	-Illness -water shortages -Heat stress	Amsterdam, London
1758	-	1		
1759	-	1		
1762	-	1		
1773	-	1		
1776	-	1		
1777	-	1		
1778	-	1	-Premature leave fall -Grass and fields withered -No second grain harvest -Water shortage -No vegetable in gardens - Tubers, coleseed, cabbage and asparagus are largely lost. - Corn harvest is good. (ready on August 20th) -City fires due to thunder and drought	Brussel
1779	-	1	-City fire Rotterdam, fire extinguishing water shortage - Empty rain trays -Water wells dried out -Rivers very low -Harvest grain and fruit abundantly -Good wine year	
1780	-	1		
1781	9	3	Trees and fruit and grain are damaged	
1782	-	1	Grass and buckwheat growth limited cattle died (food shortage)	
1783	9	2	Grass and buckwheat growth lags behind	
1784	-	1		

Annex H

Table 5: PDSI values of the driest years since 1901 (except 2018). The values below -1 are colored in orange. Source: Climate explorer (2018a).

Year	January	February	March	April	May	June	July	August	September	October	November	December
1911	-0,31	-0,38	-0,17	-0,50	-1,10	-1,10	-2,16	-3,34	-3,82	-3,35	-3,69	-3,78
1921	-2,82	-3,30	-3,66	-3,89	-4,11	-4,36	-5,26	-5,42	-5,86	-6,41	-7,14	-7,62
1959	3,14	-0,83	-0,85	-0,85	-1,78	-2,33	-2,95	-3,38	-4,56	-4,60	-5,72	-6,32
1976	-3,06	-3,17	-3,31	-3,76	-3,88	-4,72	-5,09	-6,01	-5,90	-6,07	-6,47	-7,06
2003	2,26	-0,56	-0,93	-1,06	-0,80	-1,42	-2,04	-3,21	-3,65	-3,31	-4,29	-4,61

Annex I

Table 6: Heatwaves since 1901. The heatwaves with a duration ≥ 10 days are marked in red. Source: KNMI (2018d)

Year	Date heatwave	Duration heatwaves	Number of tropical days (at least 30°C)	Highest temperatures in °C	Hottest day
1911	8 aug t/m 14 aug	7	5	33.0	10 aug
1922	21 t/m 25 mei	5	3	32.8	24 mei
1923	5 juli t/m 14 juli	10	5	33.1	11 juli
1941	20 juni t/m 26 juni	7	3	32.0	23 juni
1941a	6 juli t/m 13 juli	8	6	32.2	12 juli
1947	14 aug t/m 21 aug	8	3	32.2	16 aug
1948	26 juli t/m 30 juli	5	4	31.3	28 juli
1975	29 juli t/m 15 aug	18	6	32.9	8 aug
1976	23 juni t/m 9 juli	17	10	34.9	3 juli
1982	29 juli t/m 4 aug	7	4	31.9	2-aug
1983	4 t/m 12 juli	9	3	33.0	11-jul
1990	26 juli t/m 4 aug	10	3	35.3	4-aug
1994	19 t/m 31 juli	13	5	34.1	24-jul
1995	29 juli t/m 3 aug	6	3	32.3	31-jul
1997	5 t/m 13 aug	9	5	32.1	13-aug
1999	28 juli t/m 4 aug	8	3	31.4	1-aug
2001	22 t/m 26 aug	5	3	31.1	25-aug
2003	31 juli t/m 13 aug	14	7	35.0	7-aug
2004	2 t/m 11 aug	10	3	32.5	9-aug
2005	18 t/m 24 juni	7	3	32.8	20-jun
2006	30 juni t/m 6 jul	7	3	32.0	4-jul
2006a	15 t/m 30 juli	16	8	35.7	19-jul
2013	21 t/m 27 juli	7	3	32.6	22-jul
2015	30 juni t/m 5 juli	6	3	33.1	1-jul
2018	15 jul t/m 27 jul	13	4	35.7	26-jul-18
2018	29 jul t/m 07 aug	10	4	33.9	7-Aug-18

Annex J

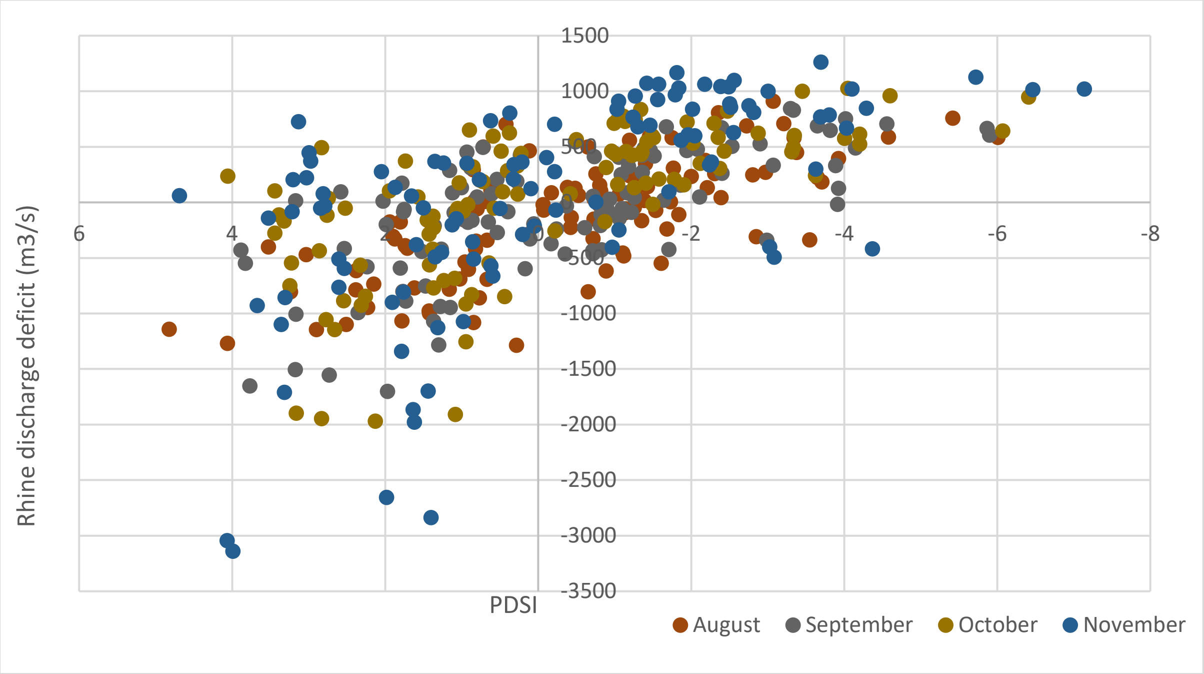


Figure 4: Mean Rhine discharge and PDSI number from August to November in the Netherlands (1901-2005)

Annex K

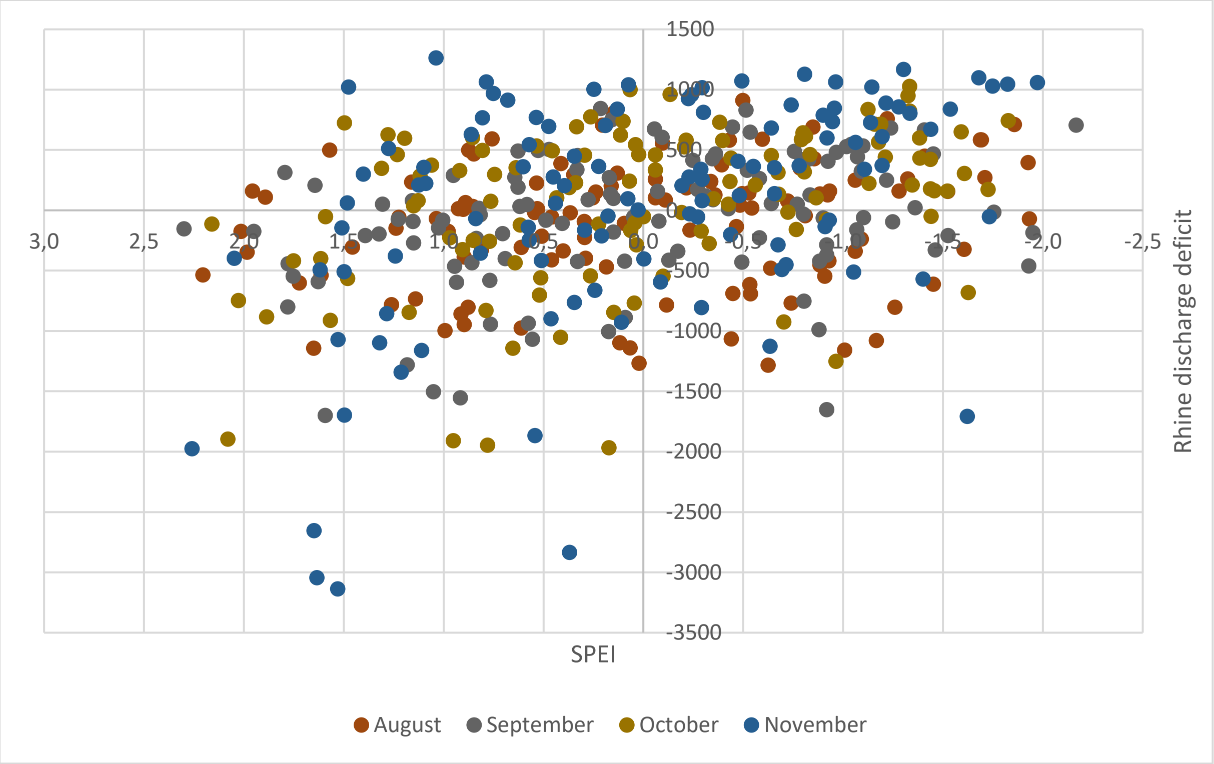


Figure 5: Mean Rhine discharge and SPEI number from August to November in the Netherlands (1901-2005)

Annex L

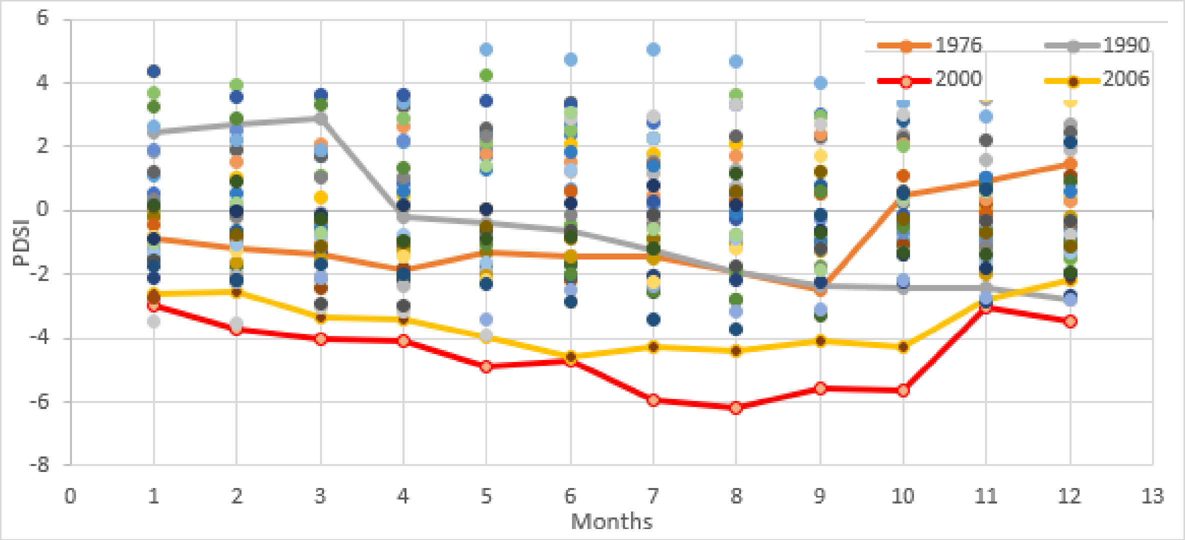


Figure 6: Mean PDSI values per month in county Orleans, Louisiana (1975-2010). Showing the two most dry years 2000 and 2006 according to PDSI values and shows the two driest years according to the precipitation deficit.

Annex M

Table 7: Mean Maximum temperatures per month of the driest years in New Orleans (°C)

	1963	1988	2000	2006	2011	Average (1971-2000)
January	14,1	14,5	18,6	20,5	15,8	16,6
February	15,3	17,1	21,5	19	19,1	18,5
March	25	21,1	24,3	23,6	24,3	22,2
April	28	25,6	26,1	28,3	28,3	25,5
May	29,7	29,4	31,6	30	30,2	29,3
June	31,6	30,8	32,1	33,7	34,5	31,9
July	21,3	23,8	20,2	21,3	22,9	21,6
August	28,2	25,3	26,7	26,8	26,6	26,5
September	30	30,3	30,7	30,7	30,3	30,6
October	32,5	31,7	34,2	32,9	35,5	32,82
November	31,9	32	34,2	32,6	33,1	32,8
December	13,2	19,2	14,8	17,2	19	18

Table 8: Monthly Precipitation rates of the driest years in New Orleans in millimeters

Month	1963	1988	2000	2006	2011	Average (1971-2000)
January	132,4	95,1	57,2	75	104	149.1
February	149,9	287,3	46,1	80,3	42	138.9
March	25,4	226,2	61,2	16,1	266,2	133.1
April	46,8	235	28,9	96,1	8,9	127.5
May	80,6	42,7	1,8	7,1	19,8	117.3
June	105,9	286,4	138,8	70,7	119,3	173.5
July	162,7	172,5	35,1	123,4	330,1	157.5
August	54	191,3	59,7	170,1	40,9	156.2
September	186,9	149	165	120	337,1	140.0
October	0	72,9	27,9	82,4	5,6	77.5
November	199,3	32	297,7	69,8	80,7	129.3
December	133,5	100,1	68,8	254,9	33	128.8
Total	1277,4	1890,5	988,2	1165,9	1387,6	1628,7

Annex N

Table 9 Heatwaves in New Orleans (1948-2019)

Year	Date heatwave	Duration heatwaves	Number of tropical days (at least 30°C)	Highest temperatures in °C	Hottest day
1948	05 April/13 April	9	3	31.1	08 April
	16 April/ 05 May	20	9	32.8	28 April
	07 May/ 02 September	119	103	36.1	31 July
	05 September/ 12 Septembr	8	5	32,8	09 September
	14 September/ 27 September	14	6	32,2	23 September
1949	23 April/ 29 September	160	125	35,6	30 June
	03 October/ 25 October	23	11	31.7	07 October
1950	25 April/ 05 June	42	19	32,2	29 May
	07 June/ 08 October	124	101	35,6	27 June
1951	24 April/06 May	13	6	30,6	06 May
	09 May/ 06 October	151	127	37,8	14 August
	25 October / 31 October	7	3	30,6	30 October
1952	27 April/ 10 May	14	10	33,3	06 May
	12 May 19 / 06 October	148	113	35,6	14 June
1953	22 April/ 04 May	13	3	31,7	30 April
	07 May /06 October	153	121	37,2	19 June
	08 October /25 October	18	4	30	17 October
1954	18 April /02 May	15	5	30,6	02 May
	27 May /	141	129	37,8	30 June

	14 October				
1955	11 April/ 07 October	180	148	35,6	23 August
1956	27 April/ 02 May	6	3	30,6	01 May
	04 May / 11 June	39	24	34,4	09 June
	13 June/ 29 September	109	89	35,6	09 August
1957	07 May/ 27 September	144	119	36,1	10 July
1958	19 April/ 05 May	17	4	32,2	24 April
	07 May/ 30 September	147	112	35	29 July
1959	25 April/ 11 May	17	7	31,7	09 May
	13 May/ 12 September	123	103	34,4	30 June
	14 September/ 14 October	31	21	32,8	05 October
1960	19 April/ 30 April	12	3	30	29 April
	15 May/ 27 September	136	122	36,1	30 July
	29 September/ 19 October	21	7	31,7	03 October
1961	03 May/ 08 May 1961	6	3	30,6	08 May
	12 May/ 26 May 1961	15	8	31,1	23 May
	28 May/ 18 June	22	16	32,2	12 June
	20 June/ 14 September	87	68	34,4	02 August
	17 September/ 02 October	16	13	32,8	25 September
1962	26 April/ 21 October	179	150	36,1	08 August
1963	11 March/ 19 March	9	3	30,6	19 March
	08 April/ 30 April	23	7	31,1	10 April

	03 May/ 23 September	144	119	36,1	14 June
	01 October / 28 October	28	8	31,7	09 October
1964	15 April/ 31 May	47	20	33,3	28 May
	02 June/ 04 October	125	103	35,6	31 Augustus
1965	01 May/ 24 September	147	106	34,4	21 July
1966	11 May/ 20 May	10	4	31,1	17 May
	22 May/ 30 September	132	97	36,1	09 July
	03 October/ 15 October	13	3	31,7	09 October
1967	27 March / 26 April	31	7	31,1	23 April
	04 May/ 20 May	17	6	31,7	14 May
	23 May/ 04 September	105	84	36,7	27 June
	06 September/ 27 September	22	18	31,7	20 September
1968	05 May / 11 September	130	113	35,6	29 July
	13 September/ 03 October	21	10	31,7	21 September
1969	10 May/ 13 October	157	120	36,7	03 July
1970	12 April/ 01 May	20	8	31,1	30 April
	05 May/ 09 October	158	117	36,7	04 July
1971	10 April/ 12 May	33	11	32,2	11 May
	15 May/ 09 October	148	122	35	14 June
1972	10 April/ 25 April	16	6	30,6	20 April
	13 May/ 30 September	141	125	35,6	05 August
	02 October/ 19 October	18	11	31,1	05 October
1973	17 May/ 16 October	153	132	35,6	17 July

1974	28 March/ 03 April	7	3	30	30 March
	26 April/ 25 May	30	10	30,6	16 May
	27 May/ 03 September	100	84	35,6	12 July
	08 September/ 02 October	25	13	32,8	28 September
1975	22 April/ 29 May	38	12	34,4	27 May
	31 May/ 21 September	114	88	33,9	18 August
1976	23 May/ 05 October	136	112	35	17 August
1977	27 April/ 14 September	141	114	36,1	01 July
	16 September/ 02 October	17	17	33,3	26 September
1978	14 April/ 19 April	6	3	30	17 April
	05 May/ 06 October	155	134		
	09 October / 13 October	5	3	31,1	12 October
1979	30 April/ 12 May	13	6	32,2	10 May
	14 May/ 09 October	149	118	36,1	05 July
	15 October/ 22 October	8	4	32,2	21 October
1980	28 April/ 05 October	161	138	38,9	22 August
	07 October / 18 October	12	6	32,8	17 October

1981	08 April/ 05 May	28	6	31,1	30 April
	08 May/ 19 May	12	4	32,2	18 May
	21 May/ 17 September	120	116	38,3	23 July
	20 September/ 18 October	29	16	32,8	10 October
1982	10 March/ 21 March	12	6	31,7	18 March
	24 April/ 21 September	171	147	35,6	26 August
	23 September/ 11 October	19	5	31,7	09 October
1983	11 May/ 05 June	26	11	31,7	03 June
	07 June/ 20 September	106	87	34,4	31 August
1984	24 April/ 19 May	26	6	31,7	14 May
	21 May/29 May	9	5	31,1	27 May
	01 June/ 28 September	120	79	35,6	21 Augustus
	04 October/ 01 November	29	3	30,6	16 October
1985	14 April/ 02 May	19	3	30,6	29 April
	04 May/ 26 September	146	102	34,4	05 June
	08 October 25 October	18	8	30,6	12 October
1986	24 April/ 29 August	128	105	37,8	30 July
	31 August/ 13 October	44	35	33,9	06 September

1987	17 April/ 02 October	169	130	35,6	11 July
1988	13 May/ 30 September	141	101	35,6	28 June
1989	16 April/ 09 May	24	3	30,6	26 April
	11 May/ 23 September	136	111	37,2	27 Augustus
	01 October/ 07 October	7	4	31,1	07 October
1990	09 May/ 23 September	138	120	37,8	05 August
	25 September/ 09 October	15	12	33,3	09 October
1991	10 May/ 17 May	8	6	32,8	14 May
	19 May/ 05 October	140	115	36,7	15 July
	09 October/ 15 October	7	3	32,8	12 October
1992	08 May/ 24 September	140	111	36,1	11 July
1993	03 May/ 09 October	160	123	36,7	31 July
	11 October/ 21 October	11	3	31,7	19 October
1994	17 April/ 30 April	14	6	31,1	28 April
	02 May/ 09 October	161	127	35	15 Augustus
1995	03 May/ 03 October	154	135	37,8	20 August
	05 October/ 13 October	9	3	31,1	11 October

1996	25 April/ 29 April	5	3	30,6	27 April
	01 may/ 27 September	150	125	35	23 July
1997	12 May/ 13 October	155	121	35	22 September
1998	30 April/ 08 October	162	135	37,2	28 Augustus
1999	19 April/ 29 April	11	6	32,2	28 April
	01 May	152	128	36,1	26 August
	01 October/ 17 October	18	5	31,1	13 October
2000	16 April/ 25 September	163	136	38,3	30 Augustus
	27 September/ 06 October	10	5	31,7	06 October
2001	02 April/ 16 April	15	4	30,6	12 April
	26 April/ 09 June	45	23	32,8	02 June
	11 June/ 24 September	106	99	34,4	24 July
	20 October/ 25 October	6	3	31,1	24 October
2002	12 April/ 17 May	36	23	33,3	02 May
	21 May/ 24 September	127	113	35	19 July
	27 September/ 13 October	17	8	31,7	06 October
2003	12 April/ 28 September	170	138	35	10 August
2004	16 May/ 07 October	145	121	35	01 August
	15 October / 03 November	20	12	32,2	20 October

2005	05 May/ 23 October	172	141	36,7	25 July
2006	10 April/ 13 October	186	122	36,1	15 August
	14 October/ 19 October	6	3	30,6	18 October
2007	19 April/ 17 May	29	9	32,2	13 May
	19 May/ 11 October	146	120	37,8	11 August
	13 October/ 22 October	10	3	30,6	18 October
2008	18 May/ 17 October	153	116	36,1	28 July
2009	21 April/ 10 October	173	134	38,3	24 June
2010	21 April/ 03 October	166	140	37,8	02 Augustus
	06 October/ 28 October	23	6	32,2	09 October
2011	18 April/ 03 May	16	11	31,7	20 April
	05 May/ 16 May	12	5	31,7	12 May
	18 May/ 01 October	137	120	37,8	02 July
	03 October/ 19 October	17	3	30,6	16 October
2012	05 April/ 20 April	16	3	30,6	15 April
	25 April/ 30 September	159	133	36,7	27 June
2013	12 May/	159	128	36,1	07 August
2014	03 May/ 14 May	12	5	31,1	12 May
	16 May/ 30 May	15	9	31,7	25 May
	01 June/ 03 October	125	109	35,6	23 August
	05 October/ 13 October	9	7	31,7	13 October

2015	30 April/ 02 October	156	131	37,2	29 July
	05 October/ 17 October	13	8	33,3	16 October
2016	18 April/21 October	187	155	37,8	26 June
	23 October/ 07 November	16	6	31,7	31 October
2017	06 May/ 29 May	24	5	32,2	28 May
	31 May/ 16 October	139	107	35,6	19 August
2018	27 April/ 20 October	177	157	36,7	17 September

Annex O

Figure 7: Effects of climate scenarios (2050) at drinking water intake points. Source: (Wuijts et., 2013)

Annex P

PLANTS & ECOLOGY TOUR
2 p.m. to 3:30 p.m.
Meeting Point: NORA Rain Garden at 5302 Wildair

- What do plants and ecology have to do with resilience and preventing flooding? Visit home gardens, municipal green infrastructure sites, neighborhood parks, vacant lots, and other sites throughout the neighborhood with plants experts and fellow St. Anthony residents. We'll discuss the ways in which plants are vital to new, and more sustainable, approaches to managing water in New Orleans, and how these green infrastructure approaches can help rebuild Gentilly's tree canopy, provide homes for new species of flora and fauna, lower air and surface temperatures during hot summer months, and improve both air and water quality. We'll also talk about the relationship between urban water management and coastal land loss/coastal restoration.
- Featuring St. Anthony resident and the Coalition to Restore Coastal Louisiana's Restoration Programs Director **Deborah Abibou**, as well as **Stephanie Gross,** biological science technician for the United States Department of Agriculture and a graduate of the Water Leaders Institute. Also featuring landscape architects from **Asakura Robinson** planning and landscape architecture firm, as well as **Batture Engineering.**

Annex Q

Infrastructure

Table 10: Drought impacts on Infrastructure in the Nethetlands

Impacts	Measure
Roads	
Undulating road	• Build roads on sandy foundation
Cracks in asphalt	• Repairing sewage system. • Build roads on sandy foundation • Rootbarrier
Uplift tiles (trees)	• Rootbarrier
Loose tiles	• Watering the tile paths • Replace tiles for asphalt
Side road	
Road side instability	• Use drought-resistant vegetation • Maintenance
Fires	• Mowing the roadside on time (maintenance) • Apply standard fire pits along the roads • no cigarettes and litter
railway	
Subsidence embankment	• built on sandy foundation
fire	• Mowing the roadside
Underground infrastructure	
Broken pipelines	• Repair • Maintain groundwater levels at a certain height
Broken house connections	• Repair • Maintain groundwater levels at a certain height

Table11: Heat impacts on infrastructure in the Netherlands

Impact	Measure
Melting asphalt & Track formation	• Sprinkling roads with salt • Apply heat resistant layer (ZOAB) • Thicker pavement
Bridges not able to open or close	• Keeping the bridge cool with water
Rail Splash	• Above 25 degrees more inspections. • Cooling the rails using water
signal failure	• Cooling • Extra maintenance
Fires	• Mowing the roads/ rail side in time.

Table 12: Impacts after a drought on infrastructure in the Netherlands

Impacts	Measure
Roads	
slippery	• Due to innovative road surface construction (including soab) and road cleaning, risk has declined sharply.
Drainage overflow	• Maintenance

Buildings (foundation)

Table 13: Drought impacts on the foundation of buildings in the Netherlands

Type foundation	Impacts	Measures
Steel foundation	Tearing of walls	• Reduce the effect of subsidence
	Subsidence of building	• Maintain groundwater levels at a certain height
Wooden piles	Degradation of wooden piles	• Maintain groundwater levels at a certain height
	Negative adhesion	• Maintain groundwater levels at a certain height
	Tearing of walls	• Reduce the effect of subsidence
Concrete slab	Tilting of the house	• Maintain groundwater levels at a certain height

Levees

Table 14: Drought impacts on levees in the Netherlands

Impact	Measures
Shrinking cracks (drought, evapotranspiration & increased rooting)	• Regularly inspections • Level up levee using soil with maturation factor near 0,7. • Preventative irrigation
Dehydration due to vegetation	• Planting grass instead of trees (+ stability increase)
Stability decrease (increase difference hydraulic heads, dehydrated vegetation, cattle and fires)	• Maintain groundwater levels at a certain height • Remove cows and sheep from the levee

Nature (Rivers, small streams and lakes)

Table 15: Drought impacts on river water the Netherlands

Impact	Measures
Limited fresh water supply	• Create fresh water buffer in wet periods • KWA • Displacement series
Limited navigation	-
Increase salinization	• KWA • Fresh/salt water separation system (bubble screen) • Locks open to a limited extent
Drinkwater risk (high concentration pollutants & medicines)	• Improve drink water treatment systems • Stronger regulation of dumping waste in rivers • Investigating alternative water resources, like grey water/ more extensive purification by sewage treatment plants. • Circular water cycle

Table16: Drought impacts on small streams and lakes in the Netherlands

Impact	measures
Decline O2 (low water=> fish mortality)	• Pumping ground water or surface water from elsewhere. • Water buffer for flushing
Dried out streams (fish mortality)	• Less water withdrawal • Rainwater retention • Allow higher groundwater levels as water storage for dry periods

Table 17: Heat impacts on small streams and lakes in the Netherlands

Heat NL	**Measures**
Odor nuisance	• Create artificial flow and connections with other water ways
Blue algae	• Decrease nutrients (almost not feasible) • Adding small amount of hydrogen peroxide • Create artificial flow
Botulism	• Good water circulation
O2 drops (fish mortality)	• Catch protected species • Create good water circulation
Increase algae bloom	• Create good water circulation
Swimming water quality declines	• Create good water circulation

Nature (Vegetation)

Table 18: Drought impacts on vegetation in the Netherlands

Impacts drought on vegetation NL	**Measures**
Leaf fall	• Maintenance and secure freshwater availability
Fruit fall	• Maintenance and secure freshwater availability
Tree bark release	• Maintenance and secure freshwater availability
Withered grass	• Maintenance and secure freshwater availability
Plant diseases	• Maintenance and secure freshwater availability
Soil acification	• Maintenance and secure freshwater availability
Secondary infestations	• Maintenance and secure freshwater availability

Table 19: Heat impacts on vegetation in the Netherlands

Heat NL	**measures**
Growing faster (temp+moist)	• Maintenance
Longer growing season	• Maintenance

Nature (Animals)

Table 20: Drought impacts on larger animals in the Netherlands

Drought NL	**Measures**
Drinking water shortage	• Some pools filled up with water by the nature managers on a regular basis (Peters, 2004)

Human Health

Table 21: Heat impacts human health in the Netherlands

Impacts	
Heat stress	- National heat plan - Green infrastructure - Blue infrastrucure - Airconditioning - Education
Oak processionary caterpillar	- Natural enemies (wasp, certain beetles, great tits) - Organic poison and mini worms
Vector born/ water born diseases	- Mosquito repellent plants like lemongrass, lavender and citronella.
Harvest bug	- Inform people
Decline water quality	- Increase flushing possibilities
Smog	- Inform people - Monitoring and reducing emissions

Annex R

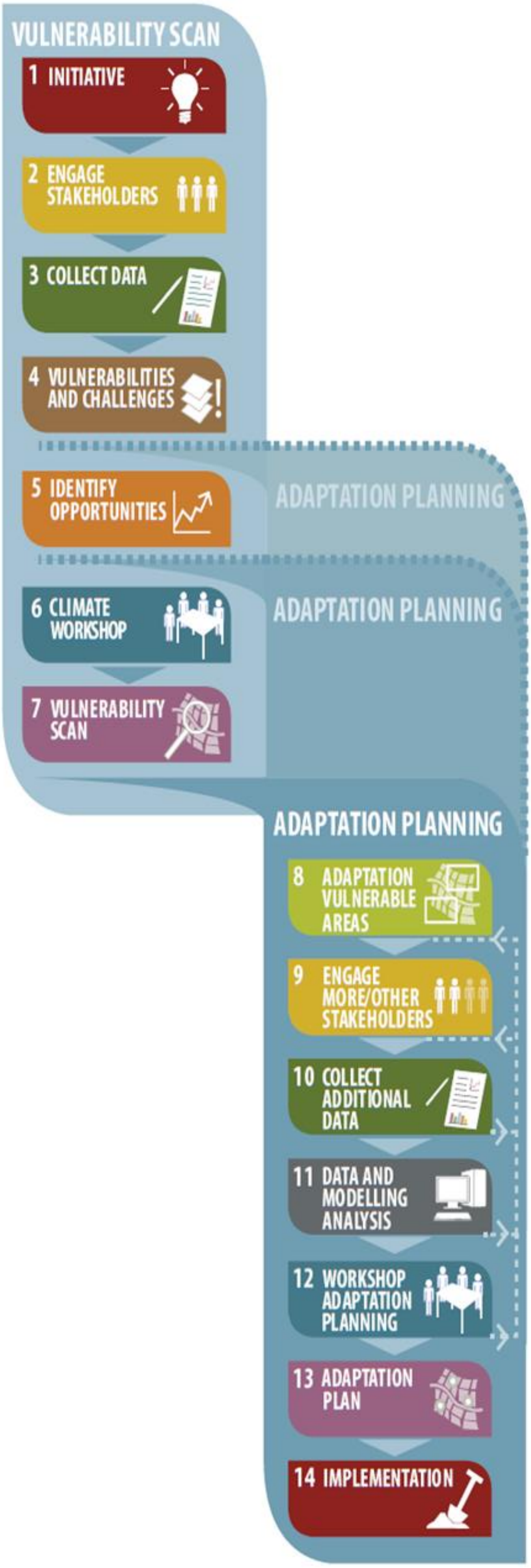


Figure 8: Stress test for climate adaptation which is used in the Netherlands

The new Dutch climate 'stress test'

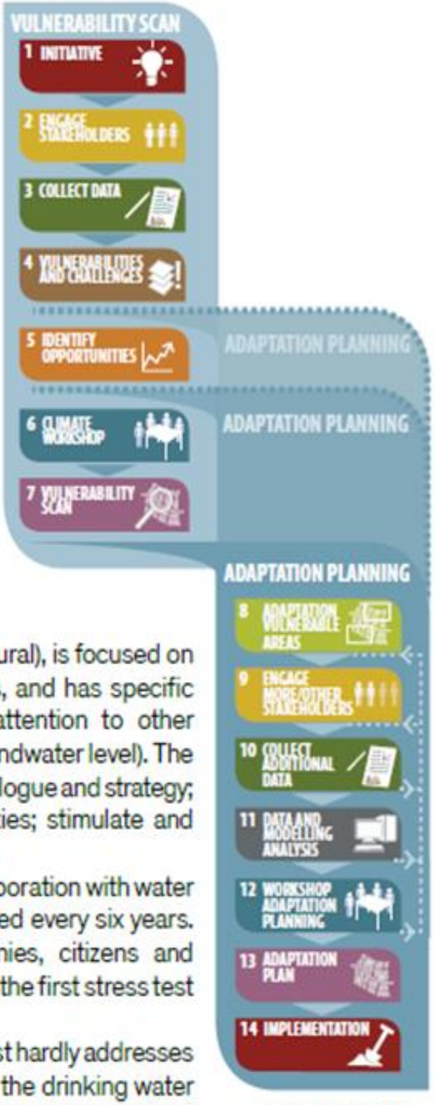
The (Dutch) stress test is intended to determine the urban vulnerability for weather extremes. The results form the basis for spatial adaptation. Key questions for the stress test are: How capable are we to prevent climate damage? And how capable are we in minimizing the damage in case our protection systems are overloaded by extreme weather and exposure is unavoidable?

Adaptation measures are meant to achieve this. Sustainable economic strength, social and competitive attractiveness of an urban area often is accepted reasons for starting stress testing. But other challenges such as intensified investments per hectare, increased mobility, new technologies, public health concerns or increasing public expectation of a perfectly functioning environment are valid arguments for stress testing and adaptation too. Land subsidence, a consequence of drought and low groundwater levels, aggravates our vulnerability to flooding and is therefore essentially included in our vulnerability scan and adaptation planning.

The test has a number of features: it is spatial (urban and rural), is focused on vulnerability to flooding, heat stress, droughts and floods, and has specific attention to vital and vulnerable functions and pays attention to other developments that increase vulnerability (subsidence, groundwater level). The test formulates seven challenges: the vulnerability; a risk dialogue and strategy; an implementation agenda; use matchmaking opportunities; stimulate and facilitate; regulating and securing; act in case of calamities.

Municipalities have a role to play in implementation, in collaboration with water boards and provinces. The stress tests need to be executed every six years. Subsequently, they must enter dialogues with companies, citizens and organisations. The next step is the execution. The results of the first stress test are to be delivered in 2019.

In contrast with the Californian situation, the Dutch stress test hardly addresses drinking water security. Even in 2018, the driest year ever, the drinking water resources (groundwater, surface water) were not in danger. The vulnerability of the water supply systems in California is however a logical part of a Californian stress test.

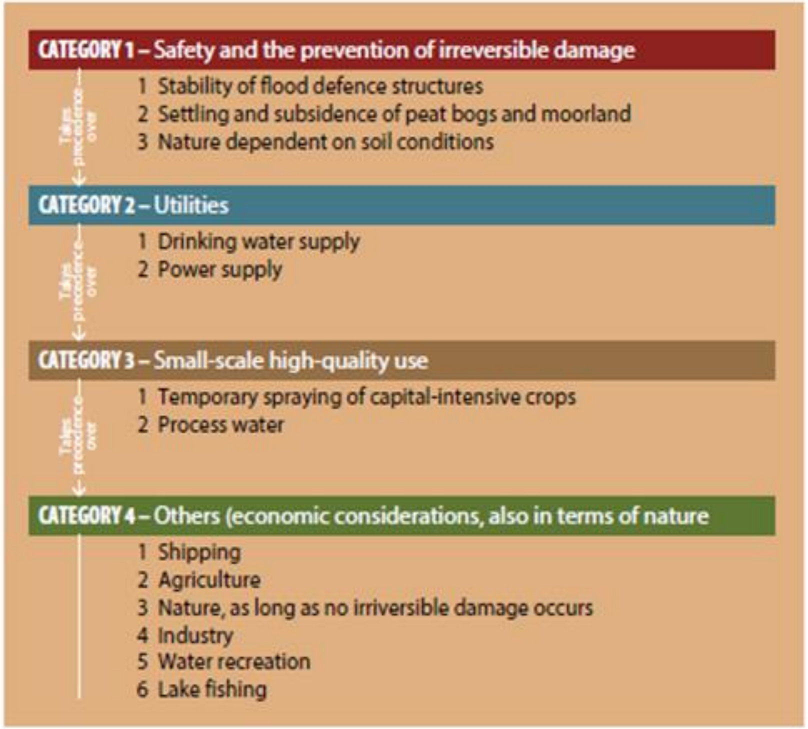


Urban climate vulnerability stress test

Drought management: de Droogte Ladder

How do the Dutch respond to periods of drought and water shortages?

Periods of drought can sometimes last so long that it is no longer possible to serve every designated use. This forces us to choose: who or what takes priority in the distribution of scarce supplies of river water? This choice is not made all over again each time but criteria are laid down in a 'sequence of priorities'. These priorities were drawn up in response to the exceptional drought of 1976, and updated after the summer of 2003 when drought was almost as intense. Unfortunately for shipping and the other sectors in category 4 the water level in rivers, canals and harbors is the least of our concerns when water is in short supply. If needs be, farmers and horticulturalists who cultivate capital-intensive crops and factories using process water (category 3) are also ignored, so as to allocate only water to the production of drinking water and to power stations (category 2). Ultimately, all that remains are the interests of the first category: safety and the prevention of irreversible damage.



CATEGORY 1 – Safety and the prevention of irreversible damage

1 Stability of flood defence structures
2 Settling and subsidence of peat bogs and moorland
3 Nature dependent on soil conditions

CATEGORY 2 – Utilities

1 Drinking water supply
2 Power supply

CATEGORY 3 – Small-scale high-quality use

1 Temporary spraying of capital-intensive crops
2 Process water

CATEGORY 4 – Others (economic considerations, also in terms of nature

1 Shipping
2 Agriculture
3 Nature, as long as no irriversible damage occurs
4 Industry
5 Water recreation
6 Lake fishing

The sequence of priorities

Acknowledgements

This thesis is the final part of my Master program in Water Science and Management at Utrecht University. During the last 8 months, I tried to understand and analyse everything about severe drought and extreme heat events and their related impacts in urban areas, in specific for the Netherlands and New Orleans.

Conducting this research without any help would have been a much harder. Therefore, I would like to write a short word of thanks to my two supervisors who guide me through the whole process of this project and for investing their time into reading and giving feedback on my thesis.

I would therefore first like to thank my supervisor Dr.Ir. N. Wanders for giving me his intellectual and technical assistance. He provided me with useful feedback to ensure that my report was kept on a scientific level.

Secondly, I want to thank R. Stuurman. He provided me the opportunity to do my research at Deltares. Without him, there was no research in the first place. I learned a lot from his extensive knowledge and his way of working. Furthermore, I am also grateful that he ensured that I was allowed to travel with him to New Orleans which was an educational and unforgettable experience.

Finally, during the trip to New Orleans, I was also accompanied by Daan Rooze (fellow intern of Deltares). He supported me among other things during the interviews and I learnt a lot of his knowledge about civil engineering, architectural and urban planning.