Knowledge for Climate

INCAH-Methodology to quantify the effects of climate change on infrastructure. An application to the effect of flooding on tunnels

CfK report number **131/2014**

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INCAH - Methodology to quantify the effects of climate change on infrastructure. An application to the effect of flooding on tunnels

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CfK 131/2014

This project (project number 034.23069; INCAH - Methodology to quantify the effects of climate change on infrastructure. An application to the effect of flooding on tunnels – INCAH WP 2.2) was carried out in the framework of the Dutch National Research Programme Knowledge for Climate. This research programme is co-financed by the Ministry of Infrastructure and the Environment.

Contents

1. Introduction

This report is written within the Knowledge for Climate research program. The research described in this report is the basis for the ICOSSAR paper [1]. In this paper the ideas and methodology explored in this report are elaborated.

Climate change and the performance of infrastructural networks

Climate changes will affect the performance of infrastructural networks. Figure 1-1 shows the levels of interaction of a network.

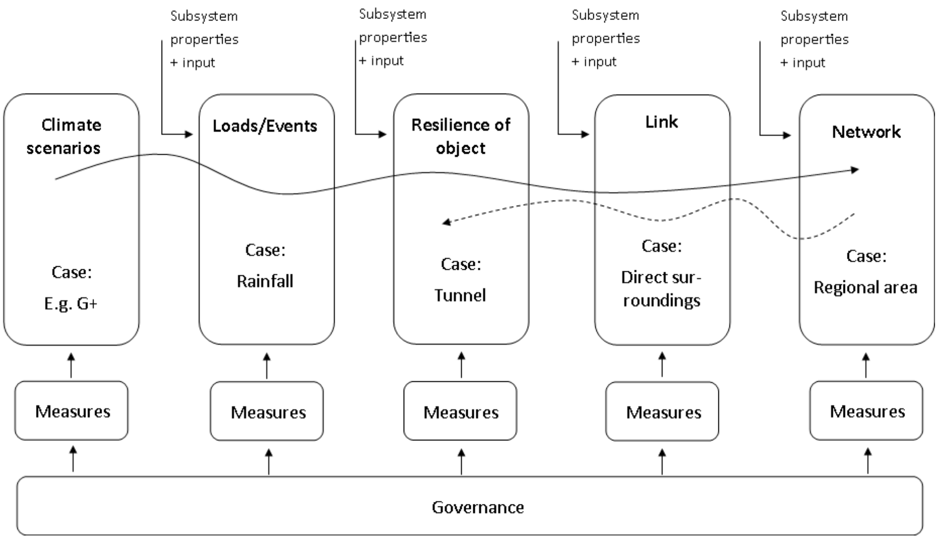

Figure 1-1 Framework interaction climate change on infrastructure

The process indicated with the arrow from left to right shows the levels of interaction. From climate scenarios loads or events can be deduced that affect the performance of separate objects in the infrastructure network. The performance of the objects will in turn affect the performance of the so-called links or nodes, i.e. the direct surroundings. This might affect the performance of the network.

The arrow from right to left describes the optimising process to improve the performance of the total network by making the individual components more robust against climate change. Ideally, road authorities know the accepted level of performance of their network, for example expressed in terms of reliability, availability, maintainability or safety (RAMS). In addition they ideally have a good understanding how all individual components of this network contribute to the overall performance. The aim would be to be able to translate the performance of the network, via the performance of the links, to a required performance of the individual components.

In order to either mitigate or adapt to climate change and improve the overall performance of the infrastructural network, measures can be applied to all levels in this scheme. For instance, measures on the climate scenario level are mitigation measures, while the others are adaptation measures.

Goal

To decide where to apply measures to either mitigate or adapt to climate change and to improve the overall performance of the considered infrastructural system, it is of importance to understand the quantitative effects of expected climate change on the performance of individual components, such as tunnels and road sections, and their contributions to the performance of the overall road network. That is, the system as presented in Figure 1-1, has to be understood.

However, a full understanding of quantitative effects on infrastructure and the effect of measures is currently lacking. Therefore, in this study, a method is developed to quantify the effects of climate change on infrastructure by performing a resilience analysis of individual objects. That is, the focus of this study is on one aspect of the system as presented in Figure 1-1.

To illustrate this method the frequency of flooding due to (extreme) rainfall induced by climate change of a fictitious tunnel in The Netherlands, is studied as a test case. This case was selected based on the results in the literature study [11]; it followed that flooding of tunnels due to rainfall might be considered as a serious threat, in terms of for example availability of the tunnel.

Approach

The diagram in Figure 1-2 shows the steps in the applied method. The process as displayed in this figure is based on the method developed by Deltares [10]. Deltares defines tipping points as points where the magnitude of change due to climate change is such, that the current strategy will no longer be able to meet the objectives. With the approach presented in the flow diagram the question “how much climate change can we cope with” or “what is the resilience of the system” is answered.

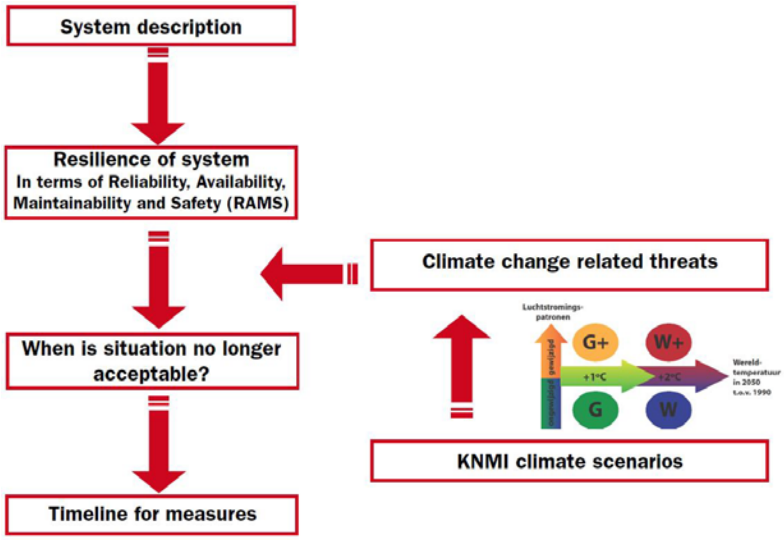

Figure 1-2 Flow diagram

First of all, an overview of typical tunnel systems in the Netherlands is presented and a system description is made, in Chapter 2. This system description is used to define a tunnel model in MATLAB[1]. This model describes the water system to drain off rain in the tunnel.

The next step is to define the conditions under which flooding of the tunnel becomes unacceptable, in terms of reliability, availability, maintainability and/or safety of the tunnel (RAMS). This topic is addressed in Chapter 3.

After that the climate change scenarios by the KNMI are considered and relevant rain data is selected and processed in a way that it serves as input for the method. This step is presented in Chapter 4.

The next step is to combine the rain data with the tunnel model, to test whether the tunnel can fulfil the RAMS requirements. The results are shown in Chapter 5.

Finally, suitable measures are selected to reduce the probability of flooding of the tunnel in order to fulfil the aforementioned RAMS requirements. This topic is presented in Chapter 6. It is noted that in case the required level of performance is known, it is possible to define appropriate measures to reduce the calculated probability of flooding. Currently this level is unknown and difficult to define. Therefore, in this report a couple of measures are described, but no ranking of the measures is performed. In addition, it is not possible to define a timeline to apply the measures, yet.

The conclusions are presented in Chapter 7.

[1] http://www.mathworks.nl/index.html

2. System description

From the literature study [11] it followed that flooding of tunnels due to rainfall might be considered as a serious threat, in terms of for example availability. See also the relation tree (Figure 2-1), showing possible climate change effects resulting in closure of a tunnel (non-availability). Investigating the effects of flooding of a tunnel due to rain was therefore selected as test case in this report to present the methodology.

In this chapter the tunnel system is described. A general description of configurations of tunnels is presented in Section 2.1. In Section 2.2 a description of the tunnel case is presented.
Note that, the tunnel characteristics that will be used in the remainder of this report are partly based on an existing tunnel and partly assumed. The results of the calculations can therefore only be used as an example.

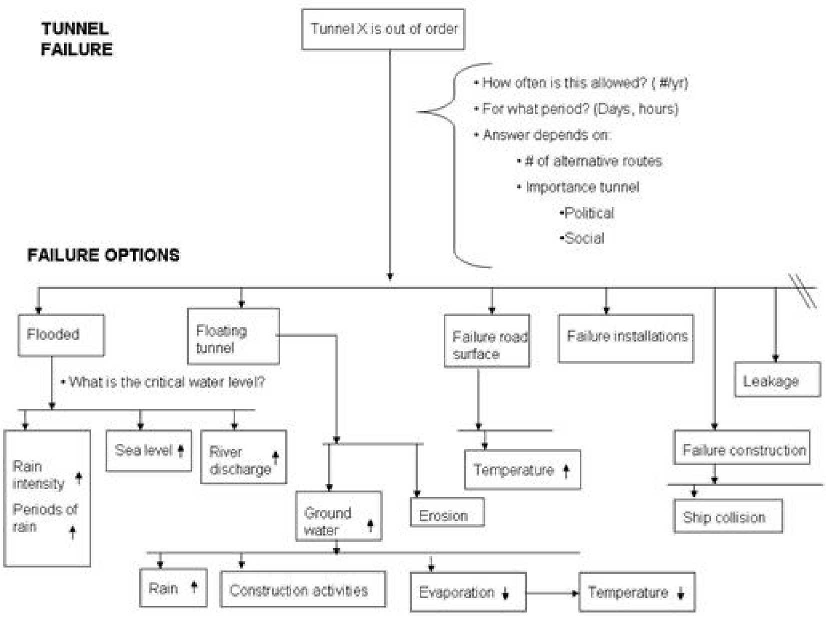

Figure 2-3 **Example of relation tree. Failure due to climate change effects.**

Tunnel systems in the Netherlands

The function of a tunnel is to accommodate underground transport. Many tunnels in the Netherlands are water crossings; crossing rivers or canals. Some tunnels cross land, either open fields or buildings. Common building methods are bored and immersed tunnels for water crossings and cut and cover tunnels for land crossings. Figure 2-2 and Figure 2-3 respectively illustrate the typical cross section of a bored and an immersed or cut and cover tunnel in The Netherlands.

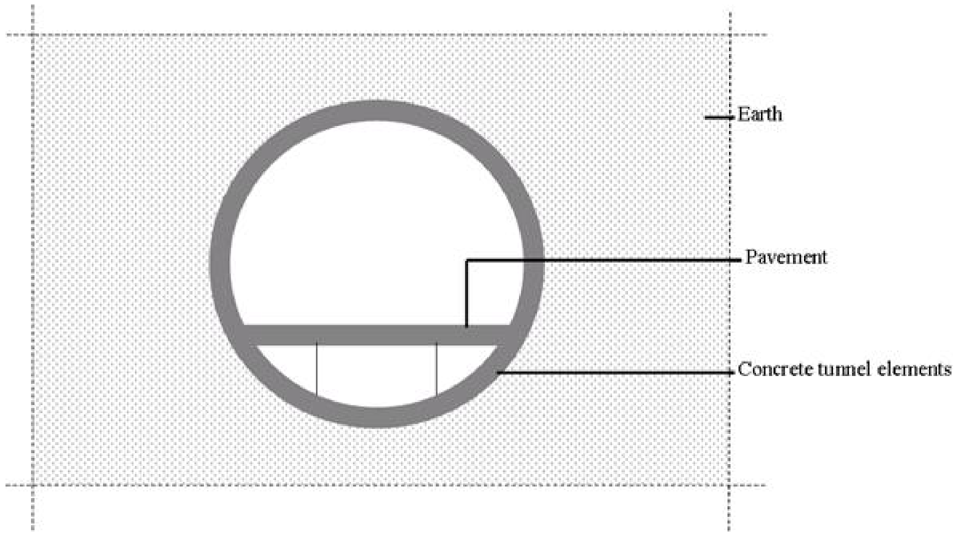

Figure 2-4 Schematized cross section of a bore tunnel

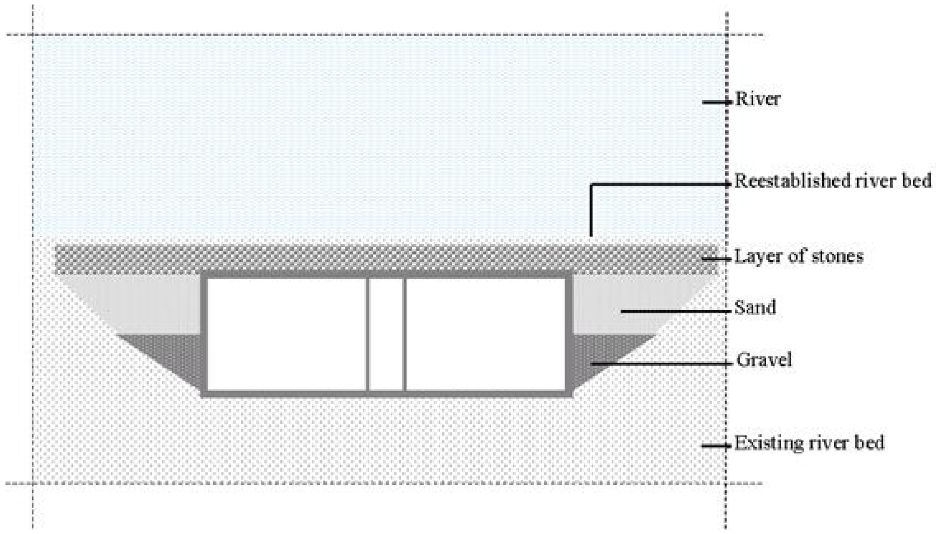

Figure 2-5 Schematized cross section of an immersed tunnel or cut and cover tunnel

Figure 2-4 shows a typical longitudinal section of a tunnel, including surrounding types of materials. From this figure, typical elements, and their function, are deduced and summarized in Table 2-1 and Figure 2-5.

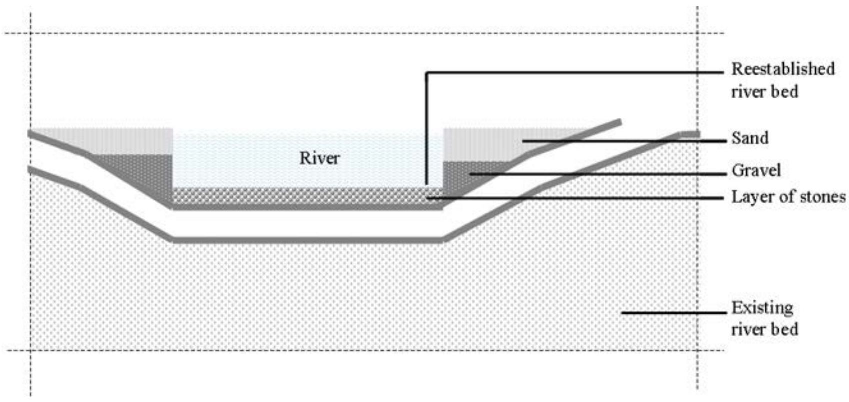

Figure 2-6 Schematized longitudinal section of a tunnel

Table 2-1 Function of general elements of tunnels

Tunnel	**To accommodate underground transport**
Element	*Function*
Ramps	To guide traffic to the tunnel and from the tunnel
Closed part	Passageway under land or water

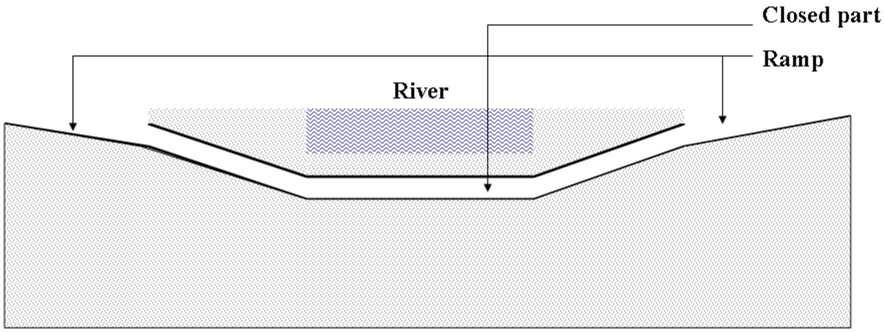

Figure 2-7 Longitudinal section of tunnel elements. Dimensions are not to scale.

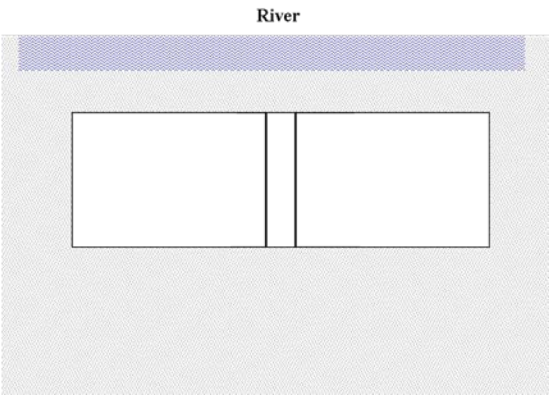

Figure 2-8 Cross section of tunnel elements. Dimensions are not to scale.

In reality, multiple systems are available to facilitate safe traffic through the tunnel.

In general, tunnels are equipped with a drainage system to store water and pump it out the tunnel system. Table 2-2 presents an overview of drainage system elements and their functions. Figure 2-7 and Figure 2-8 show a schematized lay out of the drainage system in a tunnel. Note that these schemes are not checked by the road authorities or designers. In reality, the drainage system could be different from the presented system. The lay out is an assumption, since the goal of this study is to show the different steps to be taken to define the resilience of a component, i.e. the tunnel, to climate change effects.

Multiple pump cellars are present to collect the rain. In general, main pump cellars collect water from the open parts of the tunnel and middle pump cellars (Dutch: midden pompkelder) collects water from the closed part of the tunnel. A standard drainage configuration consists of one middle pump cellar and two main pump cellars, one for each side of the tunnel.

Table 2-2 Drainage elements and their function

Drainage system	**To drain water away, to keep the tunnel available.**
Element	*Function*
Gutter	To collect the water from the surface
Drainage	To lead the water from the gutters to the pump cellars, in between pump cellars, or out of the tunnel system
Pump cellar	To store the water
Pump	To pump the water from one cellar to another or out of the tunnel system

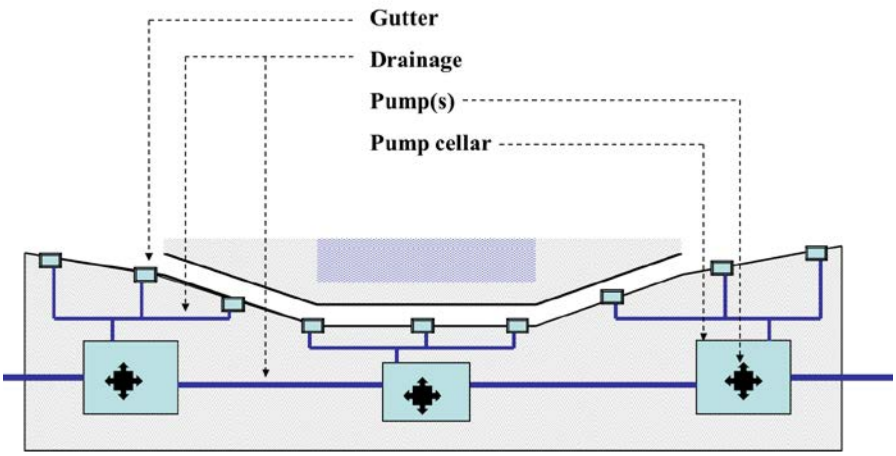

Figure 2-9 **Longitudinal section of a tunnel with drainage system. Dimensions are not to scale.**

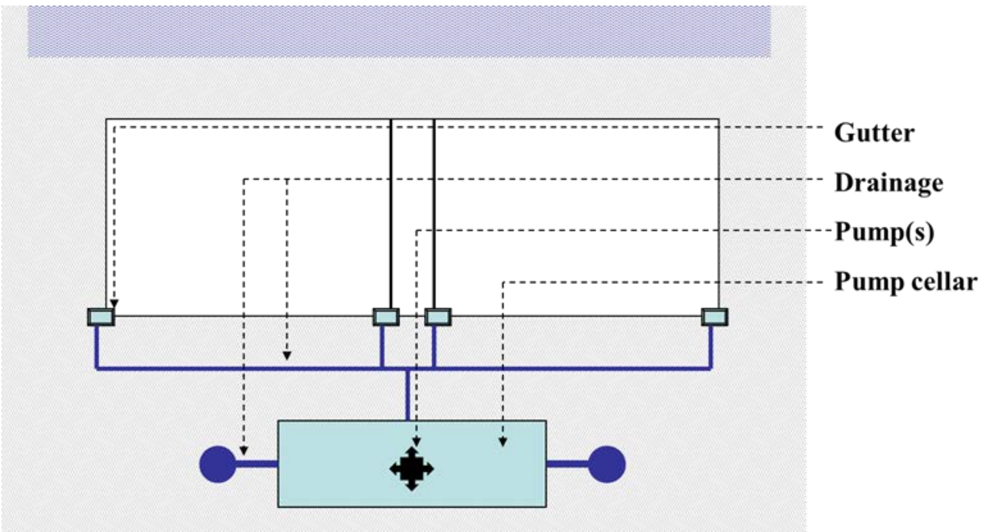

Figure 2-10 **Cross section of a tunnel with drainage system. Dimensions are not to scale.**

Tunnel case

The characteristics of the tunnel that is studied in this report are partly based on an existing tunnel and partly assumed. The results of the calculations can therefore only be used as an example.

The tunnel that is studied in this report consists of two tubes. The entrances/ramps of the tunnel are 530 m and 320 meters in length, on the east and west side, respectively. The closed (Dutch: gesloten) part of the tunnel has a total length of 547.5 meters. The width of the tunnel is 30.9 m. See Figure 2-9 and Figure 2-10 for a schematized representation of the tunnel. Table 2-3 summarizes the characteristics of the tunnel, and the drainage system in specific.

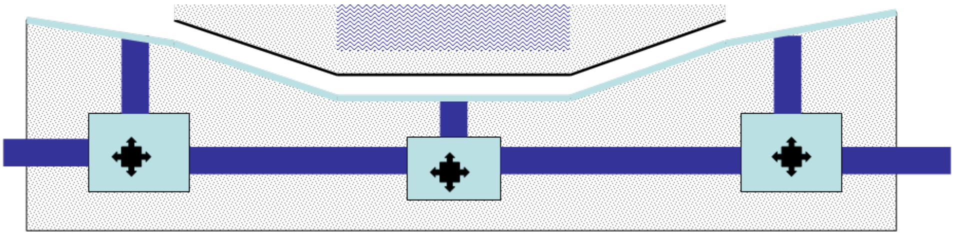

Figure 2-11 **Assumed longitudinal section of a tunnel. Drainage system is assumed to have sufficient capacity to drain the water directly to the pumps. Dimensions are not to scale.**

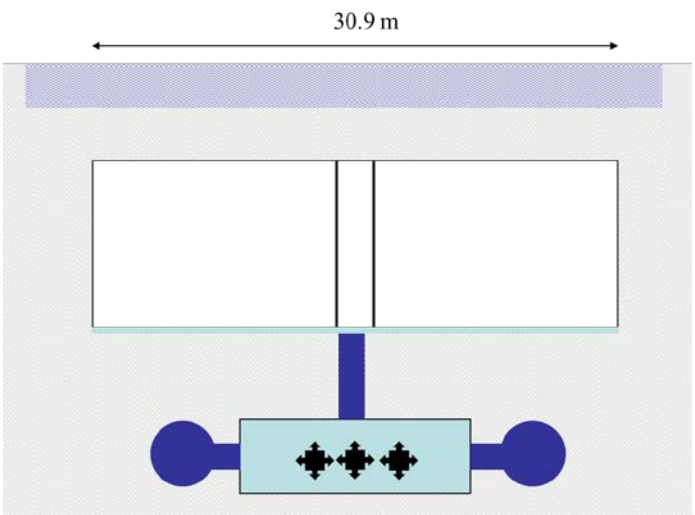

Figure 2-12 **Assumed cross section of a tunnel. Drainage system is assumed to have sufficient capacity to drain the water directly to the pumps. Dimensions are not to scale.**

Table 2-3 **Simplified lay out of the hypothetical tunnel**

Entrance west	320x30.9 m^2
Entrance east	530x30.9 m^2
Closed part tunnel	(4x115+87.5)*30.9 m^2
MiPC	71 m^3 (measured from level at which pumps are switched on)
Pumps MiPC	66.6 l/s = 3x22.2 l/s=3x1.332 m^3/min
MPC west	258 m^3 (measured from level at which pumps are switched on)
Pumps MPC west	83.3 l/s = 3x 27.8 l/s = 3x1.67 m^3/min
MPC east	258 m^3 (measured from level at which pumps are switched on)
Pumps MPC east	83.3 l/s = 3x 27.8 l/s = 3x1.67 m^3/min

When the tunnel is subject to flooding, due to heavy rain, the water will follow a certain route through the tunnel until it has been drained off to a point outside the system under consideration. The tunnel consists of multiple pump cellars. For the tunnel, a middle pump cellar (MiPC) and two main pump cellars (MPC) are available. The water which enters the tunnel via the entrance is collected in one of the main pump cellars. The water that leaks into the closed part of the tunnel (for example the water run-off of vehicles), is collected in the middle pump cellar.
Each pump cellar is equipped with three pumps to pump the water out of the cellar, and equipment to measure the water height and to switch on and off the pumps. When the water level rises and a minimum level is reached, the pumps will be started in order to empty the pump cellars. The water is pumped upwards (not included in Figure 2-7 to Figure 2-10), towards the service building or to a point where it can be drained-off to a vehicle. From the service building the water will be pumped via a pipe into the surface water. In case the water is drained-off with the help of a vehicle, the vehicle needs to be in the tunnel. Of course the capacity of the latter method is smaller compared to draining off onto the surface water.

In reality, a tunnel design will be more complicated than presented in this section. However, to illustrate the method to define the tipping points, the simplified tunnel layout is sufficient. The simplifications might affect the modelling results and may therefore be improved later on. For this study the following assumptions, concerning the drainage system, have been made:

- The collection and transport of rain via a drainage system to the pump cellars is neglected. It is assumed that water directly enters the pump cellars, i.e. the gutters and drainage system have sufficient capacity to transport the water to the pumps or outside the tunnel system. In addition, the road surface might be convex and the water will flow towards the side of the road and into openings in the barrier. Normally, behind the barrier a concealed gutter is located to drain off the water to a central collecting point. Every couple of meters larger openings are located in the barrier. The water can flow into this opening, but it is also used to clean the gutter periodically. In reality, the gutters and drainage tubes might be limiting factors in the drainage process.
- It is assumed that water that is pumped outside the tunnel system can always be stored in a river, canal or other medium. It is plausible that in situations with extreme rainfall, water can no longer be discharged to the surface water due to high surface water levels.
- Currently it is assumed that the available cellars only store rain that directly enters the tunnel system. In reality water from surrounding infrastructure might also enter the tunnel. Whether the pump cellar capacities are sufficient for this additional water, is beyond the scope of the current study.
- In case the main pump cellars are full, it is assumed that the water flows into the tunnel and fills the middle pump cellar. In case the second cellar is full, it is assumed that the tunnel will be flooded. It is assumed that the middle pump cellar pumps the water back to the main pump cellars. Finally, the water is pumped from the main pump cellars into the environment (outside scope of study).
- It is assumed that the pumps are switched on when the cellar is filled with 6 m^3 and switched off when the cellar is empty. In reality, a certain amount of water is left in the cellar, that contains for instance contaminants, sand etc.
- It is assumed that, evaporation and the effect of the slope[2] of the tunnel (a measure for the flow velocity of the water into the tunnel) are negligible and are therefore not taken into account.
- It is assumed that the cellar pumps will always function. In reality, these pump may fail due to technical defects or due to a lightning strike, for example. In this study the tunnel system is defined as a so-called deterministic system. For future research a probabilistic model, i.e. taking into account the probability of failing equipment, could be relatively easily implemented.

Capacity of system

The tunnel is modelled in MATLAB according to Figure 2-9, Figure 2-10 and Table 2-3. To gain insight in this model, the capacity of the system is analysed by exposing it to several rain durations and iteratively find the corresponding total amount of rain at which the tunnel is just able to drain off the rain without flooding. Figure 2-11 shows the capacity of the tunnel system.

[2] In the Netherlands, the maximum slope in tunnels is 4.5%.

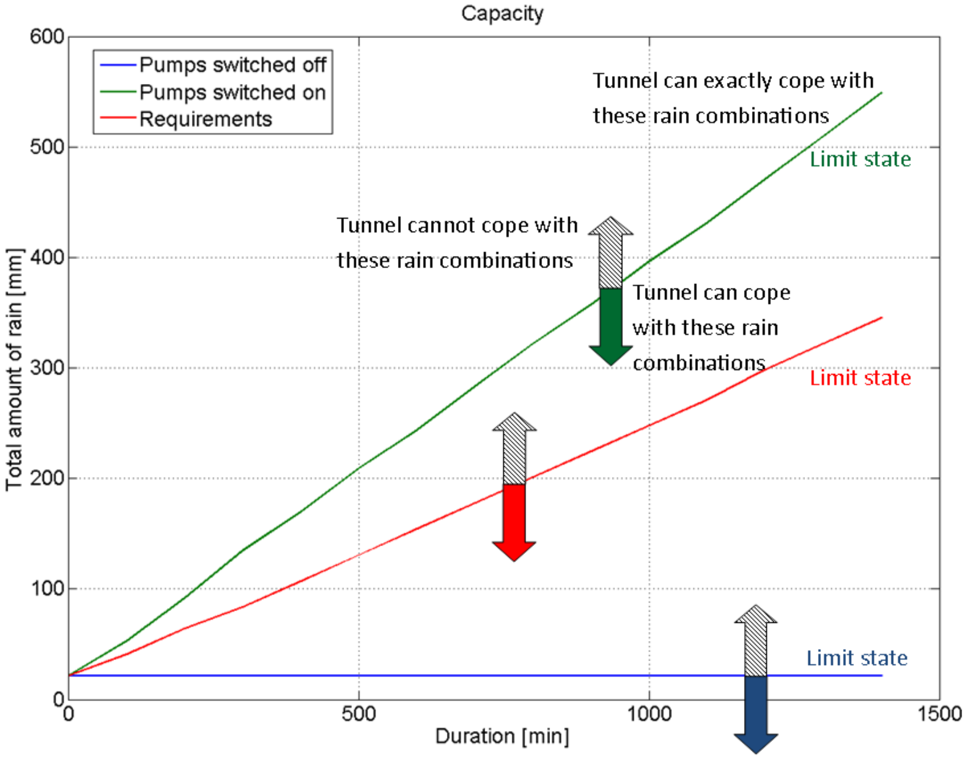

Figure 2-13 **Capacity in case the pumps are switched off (blue line), in case all pumps are switched on (green curve) and in case one pump in the middle pump cellar, and two pumps per main pump cellar are switched on (red line). The area below the lines indicates the combination of total amount of water and duration of rain that the tunnel is able to drain off. The area above the lines indicate the combination of total amount of water and duration of rain that the tunnel cannot drain off without flooding. See Table 2-3 for the tunnel characteristics.**

The blue line represents the situation that all pumps are switched off, the green line represents the situation that all pumps are switched on and the red line indicates the situation that one pump in the middle pump cellar and two pumps per main pump cellar are switched on. The latter situation is according to the required configuration to drain the water as described in [2]. The area below the line contains these combinations of total amount of rain and duration that the tunnel can cope with. The area above the line consists of the combinations of duration and total amount of rain that will lead to flooding on the road surface. From the field of probabilistic design, it can be said that the green, red and blue lines are the limit states of the system, i.e. the rain combinations that the tunnel can just cope with.

Remarks

- It must be noted that these calculations are based on continuous rainfall. For example, it is not studied if the tunnel system can handle a shower with intensity of 7 mm/min for 10 minutes, directly followed by an intensity of 2 mm/min for 30 minutes. Instead, it is studied what happens if 130 mm rain falls in 40 minutes, that is 130/40 = 3.25 mm/min.
- In addition, the drainage system is not modelled, yet. It is assumed that water on the surface directly enters the pump cellars. It can be expected, however, that especially during short but highly intense rainfall, the drainage system becomes a critical subsystem, due to its limited drainage capacity.

3. Resilience of system in terms of RAMS

A tunnel can become unavailable, and can no longer accommodate underground transport, due to several events. Examples are traffic accidents, internal failure (e.g. failure of tunnel systems) or external events. In this study the focus is on the latter, in specific climate effects. In general, to indicate all risks which may influence the performance of a system, RAMS (Reliability, Availability, Maintainability and Safety) analyses are performed. For particular tunnels in the Netherlands RA analyses have been performed [2]. A short overview of the analyses is given below (translated from [2]):

- In case it rains, the tunnel will be closed in case one of the main pump cellars fails. A main pump cellar fails in case two or more pumps fail or in case the water level measurement fails,
- In case it rains, the tunnel will be closed in case the middle pump cellar fails. This cellar fails in case all (three) pumps fail,
- Tunnels should be capable of draining the water from showers that statistically occur once per 250 years. The tunnel should be capable of draining this water by only two pumps per main cellar and only one pump in the middle pump cellar,
- The tunnel should be capable of dealing with 'regular' showers. In addition it is mentioned that the tunnel design should be such that moderate showers are drained with only 50% of the total capacity of the pumps minus one spare pump in the main cellars [2].

In addition, tunnels should be able to cope with a continuous rainfall intensity of 1.2 mm/min [18]. The guidelines prepared by RWS [18] consist of rain intensities corresponding to a frequency of occurrence of once per 250 years. These values are already adapted to climate change and were derived from a report written by Meteo Consult [6]. Currently, some discussion whether or not to use these numbers is going on. See Appendix D for these numbers.

The above listed technical requirements do give some directions for the RAMS analysis. For instance, it could be assumed that it is accepted that the tunnel has to be closed once per 250 years due to excessive rain. However, it is not stated whether no water at all is allowed on the road surface, or that a limited amount is allowed. In addition, from the literature no requirements on the duration of closure can be found. Finally, the definition of 'regular' and 'moderate' showers is not specified in [2].

Depending on the importance of the tunnel in the network, a certain period of unforeseen non-availability is probably accepted. Closure leads to traffic jams, amongst others depending on the availability of alternative routes. These consequences will influence the performance of the total network, see also Chapter 1.
An optimisation should be made for costs (or the performance of the network) caused by traffic jams and costs caused by making the tunnel more resilient. Similar optimisations can be made for the maintainability and the safety of the tunnel and their relation to the performance of the network.

The above requirements are not complete, yet. Therefore, for the tunnel case defined in this report it is assumed that no water is allowed on the road surface at all. For example, safety could be the reason to require no water on the road surface. Operators or government are to be asked to specify requirements.

4. Climate change related threats

In this chapter a short introduction is presented about the climate change scenarios and how statistical analyses are applied to derive useful rain data as input for the tunnel case.

Climate change scenarios

The KNMI [20] derived four climate change scenarios for the Netherlands based on a predicted change in worldwide temperature and air current (Figure 4-1). Relative changes around 2100 with respect to 1990 are presented per scenario in Figure 4-2.
However, from this overview no absolute numbers can be derived for 2100. In addition it is not possible to directly derive time series for rainfall with a sufficiently high resolution. That is, it is possible to translate historic time series to future series including climate change via the KNMI website. However this is on a daily base, while an hourly resolution is preferred for the tunnel case simulations.

Therefore for the tunnel case, historic rain data in Rotterdam (KNMI station number 344) was downloaded from the KNMI website[3]. In the next section and corresponding appendices it is shown how these data are processed to derive probability distributions that will serve as input for the methodology. The KNMI scenarios are used as guideline.

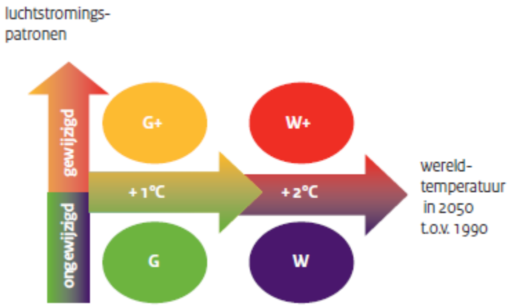

Figure 4-14 Climate change scenarios by the KNMI.

[3] www.knmi.nl

2100		G	G+	W	W+
Wereldwijde temperatuurstijging in 2050		+1°C	+1°C	+2°C	+2°C
Wereldwijde temperatuurstijging in 2100		+2°C	+2°C	+4°C	+4°C
Verandering in luchtstromingspatronen in West Europa		nee	ja	nee	ja
Winter	gemiddelde temperatuur	+1,8°C	+2,3°C	+3,6°C	+4,6°C
	koudste winterdag per jaar	+2,1°C	+2,9°C	+4,2°C	+5,8°C
	gemiddelde neerslaghoeveelheid	+7%	+14%	+14%	+28%
	aantal natte dagen (≥0,1 mm)	0%	+2%	0%	+4%
	10-daagse neerslagsom die eens in de 10 jaar wordt overschreden	+8%	+12%	+16%	+24%
	hoogste daggemiddelde windsnelheid per jaar	-1%	+4%	-2%	+8%
Zomer	gemiddelde temperatuur	+1,7°C	+2,8°C	+3,4°C	+5,6°C
	warmste zomerdag per jaar	+2,1°C	+3,8°C	+4,2°C	+7,6°C
	gemiddelde neerslaghoeveelheid	+6%	-19%	+12%	-38%
	aantal natte dagen (≥0,1 mm)	-3%	-19%	-6%	-38%
	dagsom van de neerslag die eens in de 10 jaar wordt overschreden	+27%	+10%	+54%	+20%
	potentiele verdamping	+7%	+15%	+14%	+30%
Zeespiegel	absolute stijging	35-60 cm	35-60 cm	40-85 cm	40-85 cm

Figure 4-15 Climate change in the Netherlands around 2100 with respect to the reference year 1990, according to the four KNMI'06 climate scenarios. The climate in the reference year 1990 is determined from data between 1976 up to 2005 [18].

Statistical modelling rain data affected by climate change

The starting point for deriving input for the tunnel case is historic rain data in Rotterdam (KNMI station number 344), freely available on the KNMI website[4].

Copulas

The investigation of climate change is a subject which is far from being conclusive. Therefore references are made to key aspects pointed out by previous research. In particular the probability distribution of catastrophic events is of interest. For example, the distribution of damages caused by hurricanes, tornadoes or floods. The authors of [15] examine three aspects of damage distributions: micro-correlations, fat tails, and tail dependence. In Appendix A, descriptions of these distributions can be found. In this report the focus is in particular on tail dependence. A nice concept to investigate tail dependence is the concept of *copula*. A *copula* will be understood (unless otherwise specified) as the probability distribution of two random variables (with uniform margins) together. Some introductory concepts and a statistical analysis are presented in the appendices.

Deriving input

The concept of copulas is used to derive the input for the tunnel case.
From the statistical analysis in the appendices (A, B and C) it was concluded that the so-called rank correlation between rain duration and amount of rain is 0.7 for the current rain scenario.

[4] www.knmi.nl

Not that, for this fictitious case it is assumed that climate change can be represented by adapting the rank correlation. However, this is not proved. How this adaptation of the rank correlation should exactly be made to represent climate change is not studied in this report. Instead, assumptions about the rank correlation are made, see Table 4-1. For scenario G+, G and W a lower correlation is assumed, representing more intense showers. For scenario W+ a higher correlation is assumed, representing less intense showers, according to the descriptions in Figure 4-2. These correlations are used to obtain to so-called Gumbel copula (see also Appendices A, B and C).

From these copulas random showers will be derived that serve as input for the tunnel case. In Appendix C it is explained how these random showers are derived.

Table 4-4 Assumed correlations for climate scenarios. It is not proved that the rank correlation between rain duration and amount of rain is the explanatory factor for climate change.

Scenario	Suggestion for *hypothetical* correlation/tail dependence part
No Climate Change	0.7
G+	0.6
W+	0.9
G	0.4
W	0.3

5. When is the situation no longer acceptable?

In this chapter, the rain data from Chapter 4 is combined with the tunnel model as described in Chapter 2 to test the RAMS requirements (Chapter 3). The (RAMS) requirement that is tested in this chapter is that no water is allowed on the road surface.

Current situation

As derived in Chapter 4, the rank correlation for the current climate situation is 0.7, describing the relation between rain amount and rain duration (Table 4-1). According to this number a dataset with showers was derived and tested on the tunnel case.

Figure 5-1 is the result of the simulation for the current situation. The duration of flooding (assuming that the cellar pumps are the only available means to drain the water) is presented as result of typical combinations of amount of water and duration of extreme rain (all dots). Dark blue means that the tunnel is not flooded. From this result it is deduced that the probability of flooding is $8 \cdot 10^{-6}$ per year (see also Table 5-1).

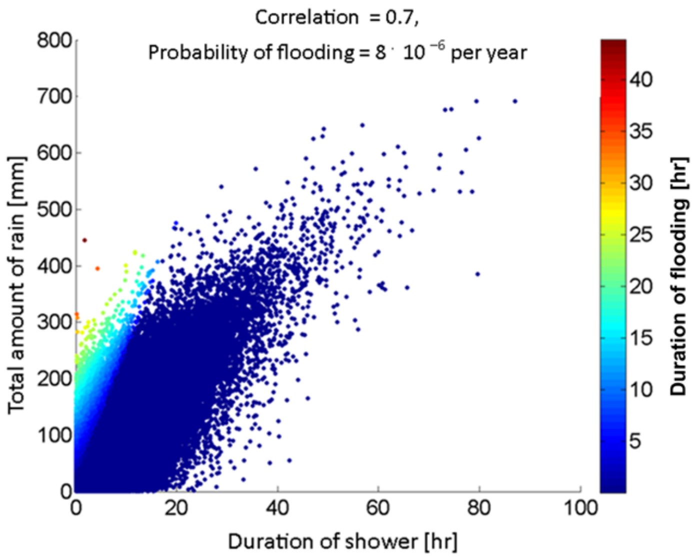

Figure 5-16 Probability and duration of flooding in current situation

Climate change scenarios

Per climate change scenario rain data sets are derived based on the hypothetical rank correlations (Table 4-1). Figure 5-2 to Figure 5-5 show the results of the simulations for the climate change scenarios.

The combination of rain duration and rain amount (that is, the shape of the dots together) is very similar for the W, G and G+ scenario. The assumed correlations between duration and amount are in these cases lower that the current 0.7. This means more intense showers. The corresponding probabilities of flooding are also higher than in the current situation, see Table 5-1.
The shape of the W+ scenario is different from the aforementioned scenarios. This is caused by the high correlation of 0.9, meaning less intense showers compared to the current situation. The probability of flooding is also less ($2 \cdot 10^{-6}$ per year) than in the current situation ($8 \cdot 10^{-6}$ per year).

Table 5-5 Probability of flooding for hypothetical climate scenarios. It is not proved that the rank correlation between rain duration and amount of rain is the explanatory factor for climate change.

Climate scenario	Assumed correlation	Probability of flooding
Current	0.7	$8 \cdot 10^{-6}$ per year
W	0.6	$1.6 \cdot 10^{-5}$ per year
W+	0.9	$2 \cdot 10^{-6}$ per year
G	0.4	$1.4 \cdot 10^{-5}$ per year
G+	0.3	$1.2 \cdot 10^{-5}$ per year

Whether or not the above presented results are acceptable is up to the operators and government. For this research it was assumed that no water is allowed on the road surface at all. This criteria is not met in this test case.

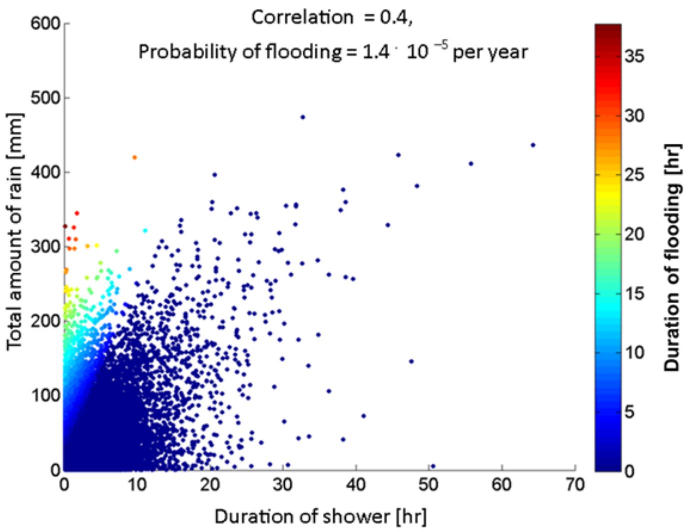

Figure 5-17 Probability and duration of flooding in climate scenario G, with hypothetical rank correlation of 0.4.

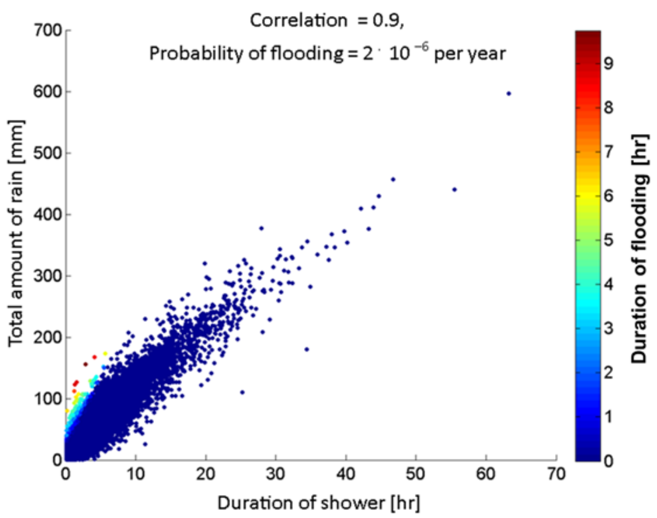

Figure 5-18 Probability and duration of flooding in climate scenario W+, with hypothetical rank correlation of 0.9.

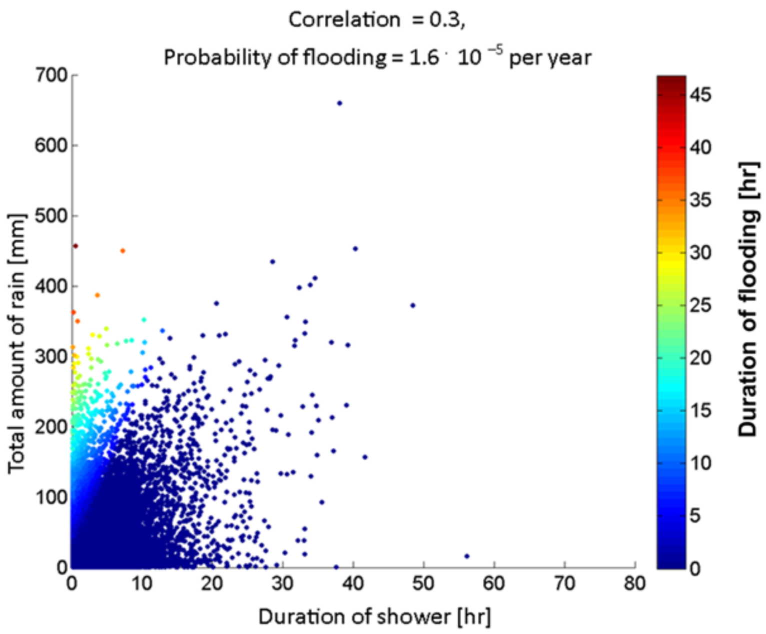

Figure 5-19 Probability and duration of flooding in climate scenario W, with hypothetical rank correlation of 0.3.

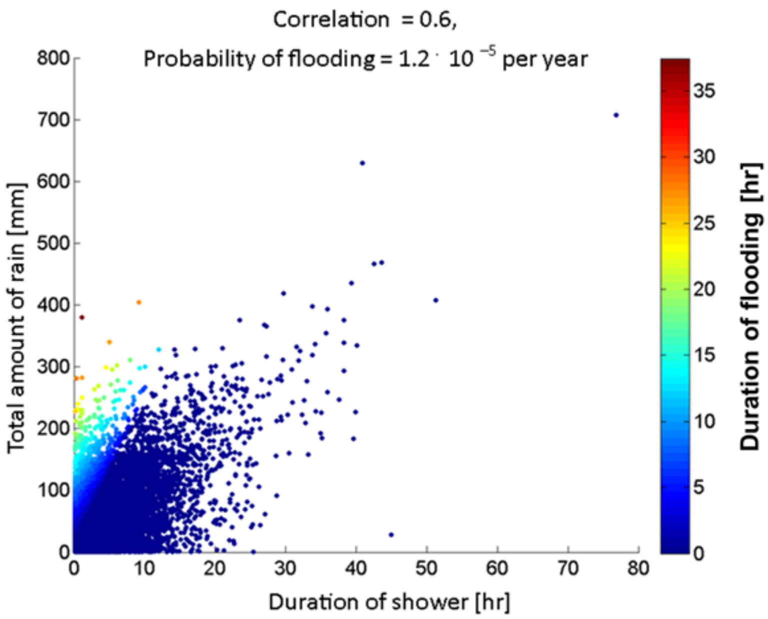

Figure 5-20 Probability and duration of flooding in climate scenario G+, with hypothetical rank correlation of 0.6.

6. Timeline for measures

In the previous chapter it was shown that in some situations the fictitious tunnel system is not able to prevent flooding in the tunnel. In this chapter possible measures are listed to increase the capacity of the tunnel system which reduce the probability of flooding. This approach will give the government and operators insight in the effect of measures. In combination with the, to be determined, acceptable probability of flooding and for example a cost-benefit analysis the responsible authorities will be supported to make decisions about measures.
Note that, in case a time line is available showing the gradual climate change a time line including measures to prevent the tunnel reaching the tipping points could be defined. However, in this study, this data is not available.

Possible measures

Possible measures to increase the capacity of the tunnel are, for example:

- Do nothing
- Increase pump capacity
- Increase cellar capacity
- Place a temporarily pump in tunnel that drains the water via a tube immediately outside the tunnel
- These measures are studied in the following subsections. Some examples are shown.

Do nothing

In case no measures are taken, the situation remains unaltered.

Increase pump capacity

The current requirement is that two pumps per main pump cellar and one pump in the middle pump cellar, should be able to drain the rain. However, per main pump cellar one additional pump is available, and in the second pump cellar two additional pumps are available. Figure 2-11 shows the capacity of the tunnel in case all pumps are activated (green solid line). It can be seen that in case all pumps are activated, the tunnel capacity increases, meaning that compared to the required configuration (red solid line), more rain can be dealt with. Table 6-1 shows the amount of flooding in case two pumps per main pump cellar and one pump in the middle pump cellar are switched on. In addition this table shows the effect on flooding in case all available pumps are switched on. The tunnel is exposed to typical rain that is expected to occur once per 250 years. It follows that the amount of flooding decreases, but that switching on all pumps is not sufficient to avoid flooding.

Table 6-6 Effect of switching on all available pumps.

Duration of shower [min]	Amount of rain [mm]	Original model	Model: additional pumps: 3 pumps per MPC, 3 pumps per MiPC
10	24	Flooding: max 29 m^3	Flooding: max 7 m^3
20	34	Flooding: max 171 m^3	Flooding: max 109 m^3
40	48	Flooding: max 405 m^3	Flooding: max 270 m^3
60	56	Flooding: max 483 m^3	Flooding: max 280 m^3
80	62	Flooding: max 507 m^3	Flooding: max 238 m^3
100	64	Flooding: max 426 m^3	Flooding: max 115 m^3

Increase cellar capacity

An expensive and time consuming measure is to increase the cellar capacity to be able to store more rainwater. Table 6-2 shows the effect on flooding in case one main pump cellar is increased with 50 m^3 and the other main pump cellar is increased with 460 m^3. These numbers were obtained by trial and error. With the immense increase of capacity, the tunnel is able to drain the typical rain that is expected to occur once per 250 years.

Table 6-7 Rain amount and duration combination that typically occur once per 250 years. Deduced from [5].

Duration [min]	Amount [mm]	Original model	Model: Additional volume: MPC west + 50 m^3 MPC east + 460 m^3
10	24	Flooding: max 29 m^3	No flooding
20	34	Flooding: max 171 m^3	No flooding
40	48	Flooding: max 405 m^3	No flooding
60	56	Flooding: max 483 m^3	No flooding
80	62	Flooding: max 507 m^3	No flooding
100	64	Flooding: max 426 m^3	No flooding

Temporarily pump in tunnel (e.g. fire brigade)

In case the current pump configuration is used (i.e. 2 active pumps per main pump cellar and one active pump in the second pump cellar), the surplus of water can be drained by installing an emergency-pump in the tunnel itself. The pump will drain the water via a tube directly out of the tunnel. The capacity of the pump depends on the time the pump is installed. In addition, a tube of a couple of hundreds of metres has to be installed. This emergency-pump can also be temporarily installed, while preparing other measures.

7. Conclusions

To decide where to apply measures to either mitigate or adapt to climate change and to improve the overall performance of the considered infrastructural system, it is of importance to understand the quantitative effects of expected climate change on the performance of individual components, such as tunnels and road sections, and their contributions to the performance of the overall road network.

However, a full understanding of quantitative effects on infrastructure and the effect of measures is currently lacking. Therefore, in this study, a method was developed to quantify the effects of climate change on infrastructure by performing a resilience analysis of individual objects.

To illustrate this method the frequency of flooding due to (extreme) rainfall induced by climate change of a fictitious tunnel in The Netherlands, was studied as a test case.

The data used is based on the climate scenarios determined by the KNMI and on historic rain data. The assumption was made that climate change can be represented by adapting the rank correlation between rain duration and rain amount. This is, however, not proved, yet. Per climate change scenario rain data sets were derived and the tunnel case was simulated. The probability of flooding in the hypothetical scenarios varied from $2 \cdot 10^{-6}$ per year up to $1.2 \cdot 10^{-5}$ per year. Whether or not these frequencies are acceptable is up to the road authorities and government. Possible measures to reduce the probability of flooding were presented.

In general it is concluded that the presented method is a promising technique that might be a good basis for decision making processes. The analysis shows that several data is missing, both climatological data as well as quantified requirements on the performance of infrastructural components.

The research as described in this report is the basis for the ICOSSAR paper [1]. In this paper the ideas and methodology explored in this report are further examined.

<u>Remarks</u>

- It is noted that the configuration of the tunnel was simplified. It must be checked whether, amongst others, the sewerage system has to be taken into account. It is expected that especially during relatively short and intense showers, the drainage system might become the limiting factor.
- The effect of introducing measures was shown, increasing the pump capacity and increasing the volume of the cellars were studied. Measures to reduce the amount of water flooding in the tunnel were not taken into account.
- An important remark is that throughout the entire study continuous rainfall is assumed. I.e. 50 mm in 60 minutes is assumed to be: 50/60=0.83 mm/min, rather than, 30 mm in first 10 minutes and 20 mm in last 40 minutes, for example. Implementing these possibilities might considerably affect the required storage capacity.

8. References

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9. Bijlagen

Bijlage A: Statistical models for environmental variables

As stated in previous chapters, two aspects of the research approach are of importance. First, an accurate and realistic model that investigates the effect of environmental variables on infrastructure has to be developed. Second, a realistic and accurate model is needed that describes environmental variables and possible climate change scenarios of interest. Previous chapters (Chapters 3 and 4) have dealt with the first. In this section the focus is on a statistical model for environmental variables.

The investigation of climate change is a subject which is far from being conclusive. Therefore references are made to key aspects pointed out by previous research. In particular the probability distribution of catastrophic events is of interest. For example, the distribution of damages caused by hurricanes, tornadoes or floods. The authors of [15] examine three aspects of damage distributions: micro-correlations, fat tails, and tail dependence.

- Micro-correlations. These are tiny correlations between variables that are easily overlooked. When many of these micro-correlations appear together, ignoring them would undermine diversification strategies. For example we could be prepared for extreme winds in some part of the Netherlands and some flooding in other parts. But how prepared are we for both appearing together?
- Fat tails lead to two main problems: (1) historical data will be a poor guide for the future, because they give inaccurate predictions for the future and (2) the tails of aggregations will also be fat, which means that the combinations of fat tails leads also to inaccurate outcomes. Mathematically this is explained by the fact that fat tailed distributions have the property that for sufficiently large x, $P(X > x) = k\, x^{-\alpha}$.
- Tail dependence. This refers to the tendency of dependence between two random variables to concentrate in the extreme values. This aspect is discussed in the remainder of this chapter.

In this report the focus is in particular on tail dependence. A nice concept to investigate tail dependence is the concept of *copula*. A *copula* will be understood (unless otherwise specified) as the probability distribution of two random variables (with uniform margins) together. Some introductory concepts are presented in Appendix B.

We will be dealing with random variables *X* "rain duration in Rotterdam" and *Y* "amount of rain in Rotterdam". From the KNMI website time series of historic weather data can be downloaded. The relative frequencies of these variables are presented in Figure A-1. The most typical type of rain duration is of only a few minutes while the typical amount of rain is also less than 20 mm (Figure A-1). From these variables rain intensity will be described. The most intense rain is naturally that in which *X* takes on low values and *Y* takes on large values.

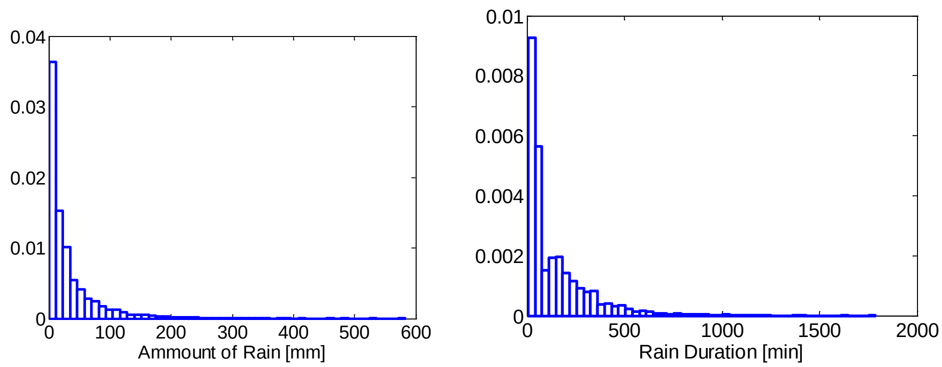


Figure A-21 Relative frequency of 'rain duration' and 'amount of rain' in Rotterdam.

Figure A-2 shows the joint relationship (joint distribution in probabilistic terminology) between "rain duration" and "amount of rain" of the historic weather data.

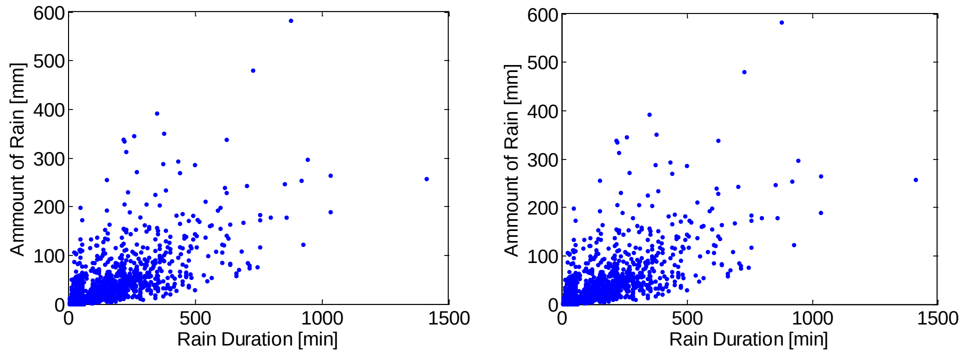


Figure A-2 Rain data between 1974 and 1993 (left) and 2001 and 2010 (right), measured in Rotterdam.

In order to model the intensity, two aspects of the environmental variables are of interest (rain amount and rain duration): their individual distribution (Figure A-1) and their joint distribution (Figure A-2).

The first task to be performed is to describe the current climate situation (the data in Figure A-1) in terms of an appropriate statistical model. Secondly, this model can be adapted to represent climate change.

In order to characterize rain intensity it is necessary to have:

- The marginal (one dimensional or individual) distributions of X “rain duration” and Y “amount of rain”. For convenience we could fit a parametric distribution to them. A common choice is the Weibull distribution (see Appendix B).
- The joint distribution or copula of the two variables.

The first problem is more familiar that the second one. Moreover the choice of an appropriate model for the joint distribution will determine the outcome of possible climate change scenarios. It turns out that the Gumbel copula described briefly in Appendix A is a model that describes appropriately the joint distribution of *X* (rain duration) and *Y*(rain amount).
Copulas are parameterized by rank correlation coefficients. The rank correlation is a number in the interval [-1, 1] that describes how values of one variable appear with variables of the other. That is how variables depend on each other. A positive rank correlation indicates that high values of *X* will appear with high values of *Y* and low values of *X* with low values of *Y*. Negative rank correlation indicates that high values of *X* will appear with low values of *Y* and low values of *X* with high values of *Y.*
The rank correlation coefficient between *X* ‘rain duration’ and *Y* ‘amount of rain’ in the case of the period of 1974-1993 is ≈ 0.7, for the case of the period between 2001 and 2010 it is ≈ 0.73. The difference between the two time series is small. Thus in the period 2001-2010 the correlation between rain duration and rain amount is quite similar to the correlation in the period 1974-1993. So no climate changes, concerning rain, are visible between both periods.

As stated previously, *tail dependence* is an important concept when modelling climate change scenarios. Under the Gumbel copula assumption, the data in Figure A-2 would have *upper tail dependence coefficient* of ≈ 0.6 and ≈ 0.62 respectively. These numbers may be interpreted as a measure of the likelihood that both random variables take extreme values at the same time. That is, extreme amount of rain tends to appear with extreme duration of rain more than average.

It was already said that the Gumbel copula is a good model for the current rain scenario. The difference in correlation (or tail dependence) observed between the periods of 1974-1993 and 2001 – 2010 is small and might be due to sampling fluctuation. Thus the whole period of interest is treated as the current scenario and the Gumbel copula is ‘artificially’ used to describe climate change scenarios. This is done to illustrate how the statistical model for environmental variables will be used in combination with the deterministic tunnel model to investigate the effects of climate change in infrastructure. It is stressed that the scenarios are meant for illustration purposes.

Bijlage B: Copulas and Dependence Measures

Representing multivariate probability distributions for certain phenomena can be a challenging task. Perhaps the multivariate model which is most widely used is the joint normal distribution. However, many phenomena behave far from normal. This is one of the reasons for researchers to have recourse to alternative models such as copulas.

Copulas are part of the building blocks of the graphical models to be used in this paper and for that reason basic concepts and definitions regarding them are introduced. The book by Nelsen (1998) presents an introduction to the subject. The book by Joe is also an important reference on the subject (Joe, 1997). Bivariate copulas will be of special interest for us. In this section by copula (or copulas) we mean a bivariate copula (or bivariate copulas) unless otherwise specified.

The bivariate copula or simply the copula of two random variables *X* and *Y* with cumulative distribution functions F_X and F_Y respectively is the function *C* such that their joint distribution can be written as:

$$F_{X,Y}(x,y) = C_\theta(F_X(x), F_Y(y))$$

Thus, a copula is a join distribution on the unit square with uniform univariate margins. Copulas are functions that allow naturally the investigation of association between random variables. Measures of association such as the rank correlation may be expressed in terms of copula (Nelsen, 1998). Notice that the copula is indexed by the parameter θ. This parameter is related to measures of dependence such as the rank correlation coefficient. The measures of association to be used in this report are described next.

The product moment correlation of random variables *X* and *Y* with finite expectations E(X), E(Y) and finite variances *var*(*X*), *var*(*Y*) is:

$$\rho(X,Y) = \frac{E(XY) - E(X)E(Y)}{\sqrt{\mathrm{var}(X)\,\mathrm{var}(Y)}}$$

Whenever possible we will denote $\rho(X,Y)$ as $\rho_{X,Y}$. The rank correlation of random variables *X*, *Y* with cumulative distribution functions F_X and F_Y is:

$$r(X,Y) = \rho(F_X(x), F_Y(y)) = \frac{E(F_X(x)F_Y(y)) - E(F_X(x))E(F_Y(y))}{\sqrt{\mathrm{var}(F_X(x))\,\mathrm{var}(F_Y(y))}}$$

The rank correlation is the product moment correlation of the ranks of variables *X* and *Y*, and measures the strength of monotonic relationship between variables. As before, whenever possible, we will denote *r*(*X,Y*) as $r_{X,Y}$. Rank correlations may be realized by copulas, hence the importance of these functions in dependence modelling. The rank correlation may be expressed in terms of bivariate copulas in the following way:

$$r(X,Y) = 12\int_0^1\int_0^1 C_\theta(u,v)\,du\,dv - 3$$

Where C_θ is the copula joining variables *X* and *Y*. In this report we will focus on the Gumbel copula. The Gumbel copula is given by:

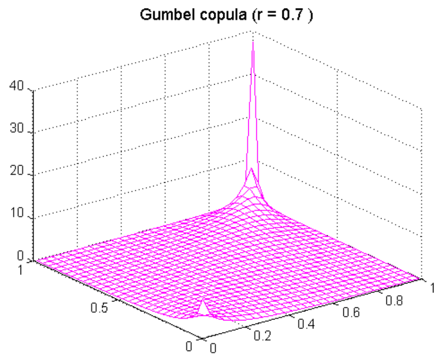
$$C_\theta(u,v) = \exp\left\{-\left[(-\log u)^\theta + (-\log v)^\theta\right]^{1/\theta}\right\}$$

One important concept in modelling the occurrence of extreme events is tail dependence. Loosely, tail dependence refers to the probability which with extreme events (for example large amounts of rain with high duration) occur together. Formally, the upper tail dependence coefficient is defined as:

$$\lambda_U = \lim_{u \to 1} P(U > u \mid V > u) = \lim_{u \to 1} P(V > u \mid U > u)$$

From the definition above one may see that the upper tail dependence coefficient is bounded to (0,1). If λ_U is positive then there is a positive probability that *U* or *V* are larger than *u* given that the other is larger than *u* for *u* arbitrarily close to 1. Similar expressions exist for tail dependence in the other corners of the unit square. The Gumbel copula has upper tail dependence and its coefficient is given by :

$$\lambda_{U,Gumbel} = 2 - 2^{1/\theta}$$



Gumbel copula density with correlation 0.7

Bijlage C: Description of rain intensity from KNMI data

For completeness, first we repeat Figure A-2 in this appendix.

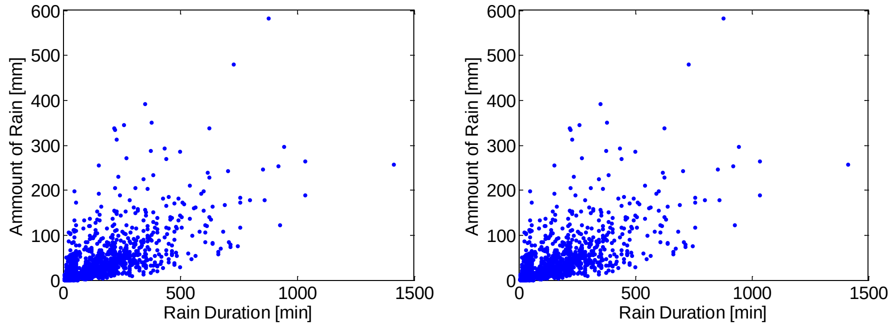


Figure C-1 Rain data between 1974 and 1993 (left) and 2001 and 2010 (right), measured in Rotterdam (similar to Figure A-2).

Both scatter plots in Figure C-1 are very similar showing positive dependence. For example large values of rain duration tend to appear with large values of amount of rain. In statistical terms this translates into a positive rank correlation.

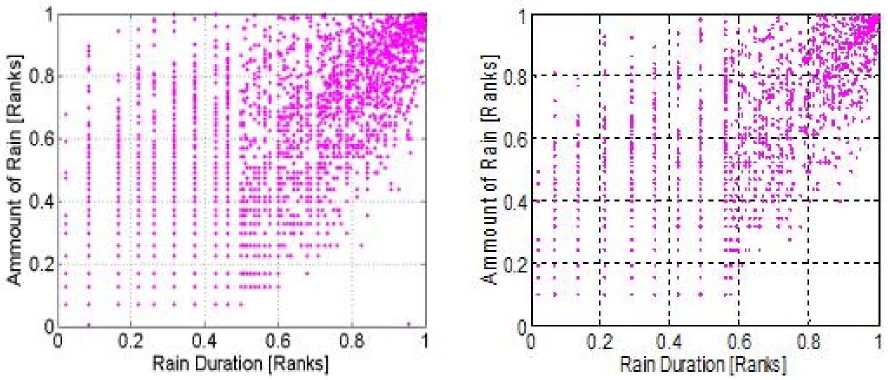


Figure C-2 Rain data (Ranks) between 1974 and 1993 (left) and 2001 and 2010 (right), measured in Rotterdam.

In order to appreciate in a different way the relationship between these variables we fist rank them and them show their scatter plots. This is shown in Figure C-2. In statistical terms this means that we "remove" the additional information conveyed by the individual distributions of each random variable. Observe that on both figures again a positive correlation (high values of one variable corresponding to high values of the other and similarly for low values). Observe additionally that there is high concentration of samples as one gets closer to 1 on both directions. This could be an indication of tail dependence. That is high values of rain duration tend to appear with high values of amount duration.

More precisely, the rank correlation coefficient between *X* rain duration and *Y* amount of rain in the case of the period of 1974-1993 is ≈ 0.7, for the case of the period between 2001 and 2010 it is ≈ 0.73

As stated before, in order to model "rain showers", that is, the relationship between *X* and *Y* we will use copulas. Thus the question of interest is which statistical model would approximate sufficiently (in a statistical sense) the observed behaviour of data?

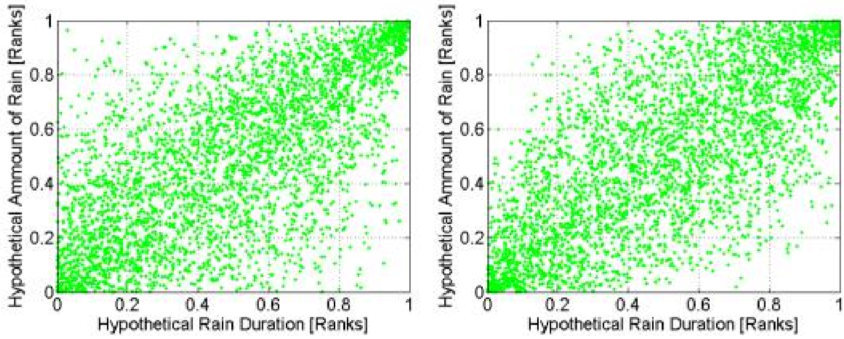


Figure C-3 Hypothetical Rain data (Ranks) generated with the Gumbel copula (Left). Sample of the Normal Copula (Right).

Two possible models that could characterize the data are presented in Figure C-3. Figure C-3 presents a sample from the Gumbel copula on the left and of the Normal or Gaussian copula on the right. The density of the Gaussian copula has a characteristic elliptical shape. This is translated in the samples in Figure C-3 on the right being distributed in the shape of an ellipse.

The Gumbel copula on the other hand tends to show its density more "spread out" in the lower quadrant of the unit square and have it "more dense" in the upper one. The last remark has to do with tail dependence. In this case, intuitively we would observe that the probability that extreme values of both variables occur together is positive. This type of behaviour is also observed in Figure C-2, thus one may argue that the Gumbel copula is a better description of the data than other models such as the Gaussian Copula.

As stated in the introduction to this chapter *tail dependence* is an important concept when modelling climate change scenarios. Under the Gumbel copula assumption, the data in Figure C-2 would have tail dependence coefficient of ≈ 0.6 and ≈ 0.62 respectively. The Gaussian copula does not exhibit tail. One may argue that this would already make it an unfortunate choice as a model for climate change scenarios. A formal statistical validation for the Gumbel copula as model for our data may be done following [21]. This has not yet been done in the present study but is recommended for future research.

Simulation of maximal showers

Roughly our approach will consist in first simulating many random showers from the Gumble copula. Each shower will serve as input for the tunnel model (section 3.1) and together these will tell something about the availability of our hypothetical tunnel. More specifically our approach will be:

Our procedure consists on the following steps:

- Select the number of simulations
- For each simulation generate approximately 1,825,000 samples of the pair (X,Y) representing maximal showers in a day. These samples represent maximal showers in 10,000 years. The 10,000 years are selected in order to ensure samples of rain with a probability of return ≥ 1000 years.
- For each of the approximately 1,825,000 number of days with rain in 10,000 years compute the level of water in the tunnel of interest.
- If flooding (water in excess to a determinate value) was observed, record:
    - The pair (X,Y). That is, maximal rain and duration.
    - The return value of the maximal rain in the day.
    - The flooding level.

Within the simulation process we will also consider parametric distributions for our data. We fit through maximum likelihood parameters for a Weibull fit for both one dimensional margins. The fits are shown in Figures 9.4.

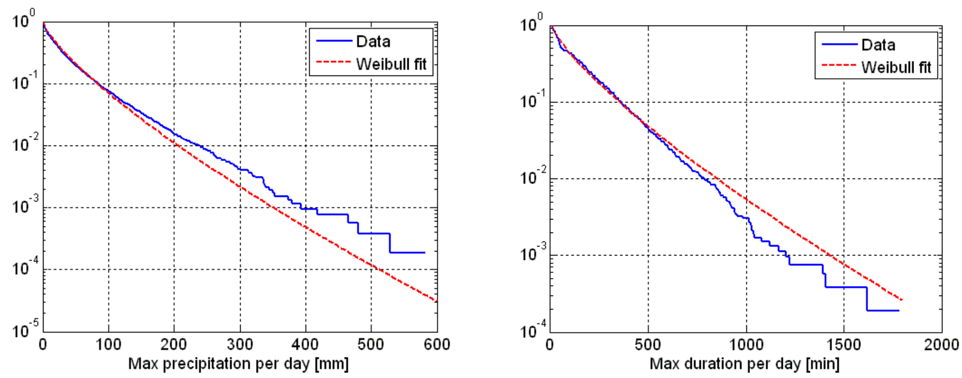


Figure C-4 **Left: Amount of rain [mm] Right: Rain Duration [min]**

The Weibull parameterization is as in Equation C.1:

$$f(x|a,b,c) = \frac{b}{a} \cdot (x-c)^{b-1} \cdot e^{-\left(\frac{x-c}{a}\right)^{b}} \cdot I_{[c,\infty]} \quad \text{(C.1)}$$

Observe that the fits shown in Figure C-4 "are better" for samples with exceedence probability less than 1/100 than for samples with larger than this probability. This is a second refinement that our model might undertake in the future, for example by considering other parametric forms. Having a parametric distribution is however of importance in order to be able to observe values larger than those observed in our period of reference.

Derivation Gumbel copulas

In order to characterize climate change through the Gumbel copula, the summer scenarios (Figure C-2) are used. This is because these scenarios show the most extreme increase in "daily accumulated rain intensity with return period of once per ten years".

In general the most threatening situations for infrastructure are those where high amounts of rain appear with low values of rain duration. For example, we are interested in those cases where a value for amount of rain (*Y*) higher than the value of its distribution of with 50% probability of occurrence (that is, its median) appears with low values of rain duration (For example those lower than the value of the distribution of rain duration with 50% probability of occurrence).

From the data one may compute the median value of rain duration as 60 minutes and rain amount as 16mm. We are thus interested in the probability that rain duration is below median (60min) given rain amount is above its median (16 mm). This is written as:

$$P(X < x_{50} \mid Y > y_{50}) = P(X < 60\,min \mid Y > 16\,mm) \quad \text{(C.2)}$$

Where x_{50} and y_{50} are the medians of X and Y respectively. Notice that the ratio $y_{50} / x_{50} = 0.2667$ [mm/min]. Thus, the probability above really asks for the probability of observing a ***shower intensity*** higher than 0.2667 [mm/min]. The probability (C.2) under the Gumbel copula assumption as a function of the rank correlation is presented in Figure C-5.

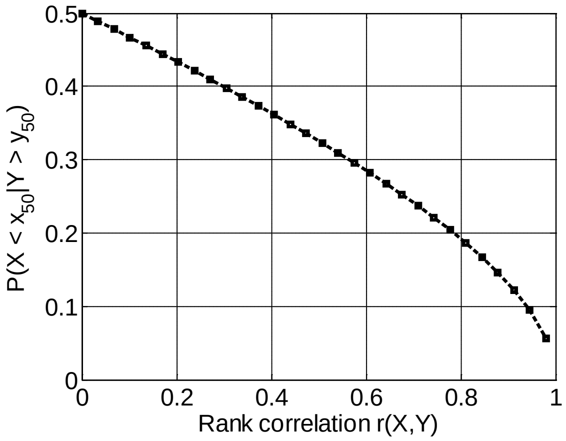


Figure C-5 P(X < x50 | Y > y50) = P(X < 60 min | Y > 16 mm) as a function of the rank correlation under the Gumbel copula assumption.

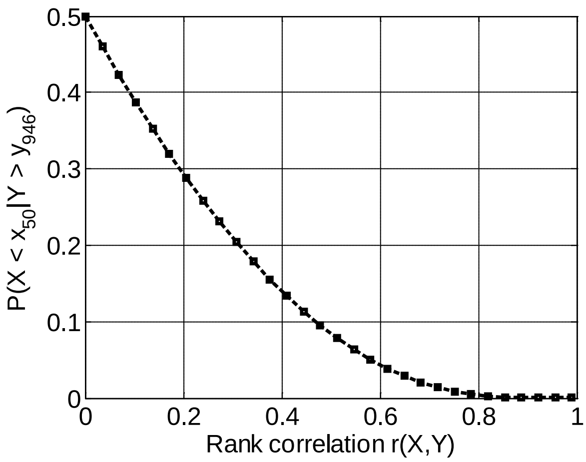


Figure C-6 P(X < x50 | Y > y946) = P(X < 60 min | Y > 120 mm) as a function of the rank correlation under the Gumbel copula assumption.

If rain amount and rain duration where uncorrelated (independent), then $P(X < x_{50} \mid Y > y_{50}) = P(X < x_{50}) = 0.5$. However, because they are positively correlated, the probability of ***shower intensity*** decreases with increasing rank correlation. Accordingly as shown in Figure C-6, with smaller rank correlations than the one observed in the data (0.7) the probability of high shower intensity $P(X < 60 \text{ min} \mid Y > 16 \text{ mm})$ increases as well. Recall that in the current situation observed from KNMI's data a rank correlation of approximately 0.7 was observed.

Suppose even more extreme probabilities of shower intensity are modeled. For example, the probability of observing a ***shower intensity*** higher than 2 [mm/min]. From the data one may see that $y_{946} / x_{50} = 2$ [mm/min]. we would be interested in observing $P(X < x_{50} \mid Y > y_{946}) = P(X < 60 \text{ min} \mid Y > 120 \text{ mm})$. We compute again this probability under the Gumbel copula assumption as a function of the rank correlation. The result is shown in Figure C-6 which has the same interpretation as Figure C-5 above.

Computing the above presented type of information becomes an easier process with the choice of a parametric model for the copula describing showers intensity. That is, the relationship between rain duration and rain amount. This example illustrates also one advantage of adjusting the appropriate parametric model to the data.

Result

For illustration purposes, the correlation parameters in Table C-1 were selected to model the climate change scenarios of interest, as already mentioned. The correlations are hypothetically chosen. The corresponding probabilities of the defined intensities can be derived from Figure C-5 and Figure C-6 and are presented in Table C-1.

Table C-1 Parameters for the Gumbel copula for selected climate change scenarios.

Scenario	Suggestion for *hypothetical* correlation/tail dependence part	Less extreme intensities $P(X < x_{50} \mid Y > y_{50}) =$ $P(X < 60\text{ min} \mid Y > 16\text{ mm})$	More extreme intensities $P(X < x_{50} \mid Y > y_{946}) =$ $P(X < 60\text{ min} \mid Y > 120\text{ mm})$
NCC	0.7	0.2416	0.01710
G+	0.6	0.2852	0.04358
W+	0.9	0.1313	0.0002
G	0.4	0.3633	0.1402
W	0.3	0.3994	0.2102

The next step consists of first simulating many random showers from the Gumbel copula as presented in this section. Each shower will serve as input for the tunnel model (Chapter 3) and together these will tell something about the availability of the tunnel.

Bijlage D: Braak's raincurves

In the Rijkswaterstaat guidelines [18] the requirements concerning tunnels and amount of rainfall can be found. A distinction is made between continuous intensity of rainfall and the so called Braak's raincurves (derived from [6]). The first is used to calculate the drainage capacity of the (tunnel) system and the latter is used to calculate the storage capacity of the system.

For tunnels a continuous intensity should be used of 1.2 mm/min. The Braak raincurve to be used is the intensity curve with a frequency of exceedance of once in 250 years. Table D-1 presents the Braak curve without correcting for climate change. Table D-2 shows the Braak curve including a climate change effect.

Table D-1 Braak curve excluding climate change exceedance frequency of 1x250 years. Data is derived from [5]; read from graph.

Duration [min]	Amount [mm]	Duration [min]	Amount [mm]
0	0	55	56
5	15	60	58
10	24	65	59
15	30	70	60
20	34	75	61
25	40	80	62
30	44	85	63
35	46	90	64
40	48	95	65
45	52	100	66
50	54		

Table D-2 Braak curve including climate change exceedance frequency of 1x250 years. Data is derived from [6].

Duration [min]	Amount [mm]	Duration [min]	Amount [mm]
0	0	55	66.44
5	21.77	60	68.74
10	30.85	65	70.89
15	37.54	70	72.91
20	42.96	75	74.8
25	47.56	80	76.59
30	54.57	85	78.27
35	55.14	90	79.87
40	58.35	95	81.39
45	61.27	100	82.84
50	63.96		