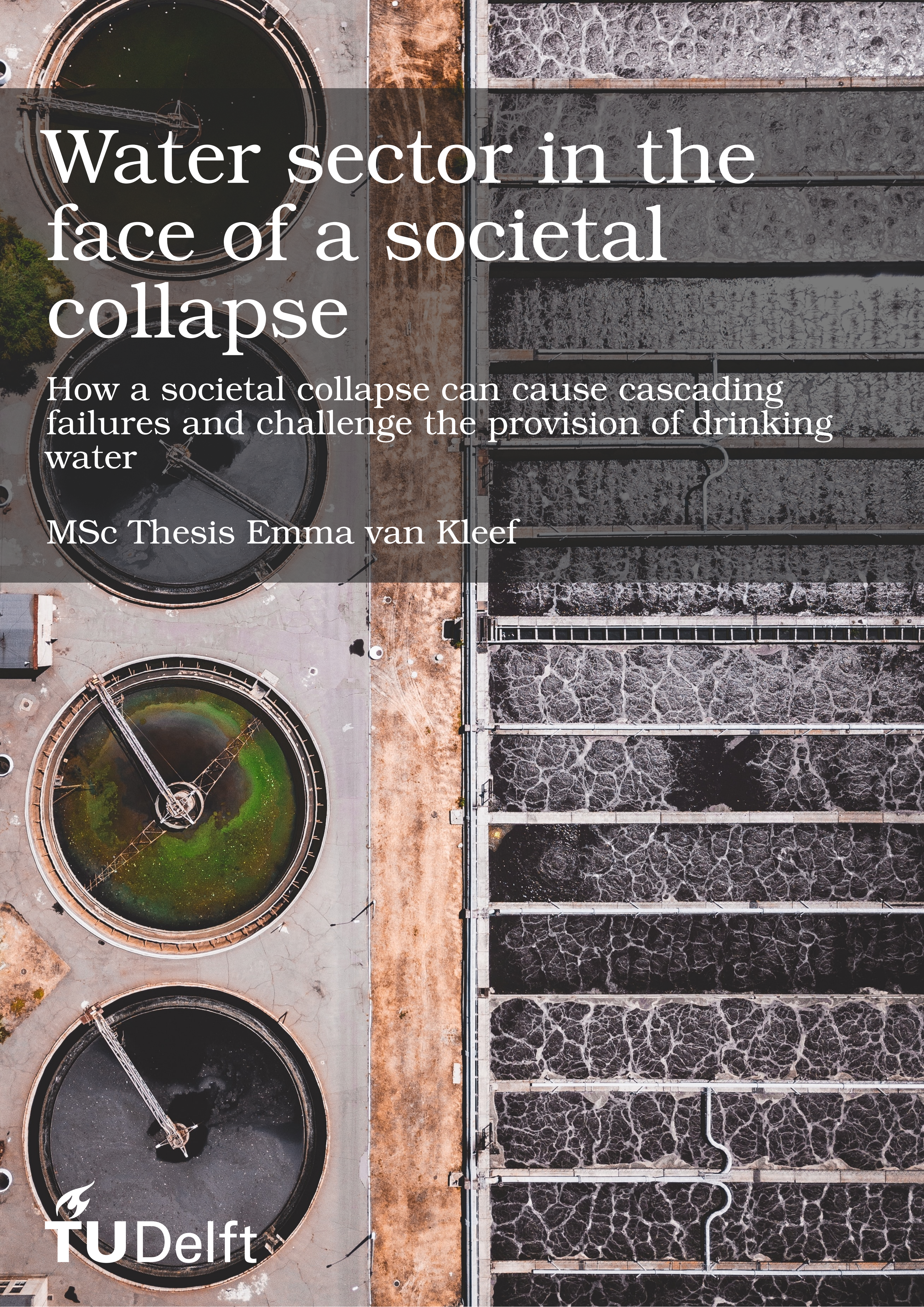


Water sector in the face of a societal collapse

How a societal collapse can cause cascading failures and challenge the provision of drinking water

MSc Thesis Emma van Kleef

TU Delft

Water sector in the face of a societal collapse

by

Emma van Kleef

Student Name	Student Number
Emma van Kleef	4664922

Graduation Committee
Dr.ir. I. (Igor) Nikolic
Dr. O. (Omar) Kammouh
Dr. U. (Udo) Pesch
External supervisors
Dr. P. (Peter) van Thienen
G. A. (Alex) Chatzistefanou MSc

Faculty of Technology, Policy and Management, Delft

Cover:
Bandura (2018)

Preface

Before you lies the research that I have been working on for the past few months. Despite its dire topic, I have enjoyed researching this thoroughly. I've learned a lot about what it really takes to do academic research, and it has challenged me beyond my expectations. It was a journey where I constantly went from being lost to knowing exactly the way to being very much lost again. And now, finally, the journey has come to an end. Although I very much encourage many policy-makers and researchers to consider collapse thinking in their design, I really hope that I will never get the opportunity to say "I told you so" to anyone!

This thesis would have never been possible without the support of my supervisors.

Thank you, Omar, for the sometimes intensive, but always insightful and helpful meetings. I appreciate your input throughout the process and always asking questions I sometimes didn't have the answers to. It taught me that I don't always have to have an answer!

Thank you, Igor, for the valuable input, and for pushing me beyond my comfort zone. Thank you for making the time to meet with me, despite your busy schedule, as soon as I figured out WhatsApp is much more effective than e-mail.

Thank you, Udo, for taking the time to read and provide feedback on the report.

Thank you, Peter, for the challenging, sometimes impossible, yet very interesting thesis topic. Thank you for your support throughout with valuable discussions, insightful comments, well-thought-out answers, and your seemingly endless knowledge of societal collapse and drinking water. I really appreciate the time you have taken to guide me through this complex project.

Thank you, Alex, for your contribution to the weekly meetings, providing good and useful feedback and enjoyable chats at the office. I wish you the best of luck with the rest of your PhD!

Thank you to the rest of the Hydroinformatics team for the enjoyable time at KWR. I have felt very welcome in the team and have enjoyed getting to know all of you over the last months. I would also like to extend a special thank you to the organization of the visit to the water treatment facility in Nieuwegein. It made my thesis topic that much more tangible, which was really needed. Thank you to all the other colleagues at KWR who met with me to discuss my work and helped me understand and process a lot of the missing pieces. I would also like to give a shout-out to Bernard from Oasen: I really enjoyed visiting the RO-facility and learning about this innovative technique in water treatment. Thanks for taking the time from writing your own thesis to organize that!

Thank you to all the interviewees for their input and valuable contribution. Thank you for taking the time to answer my questions and teaching me a lot about the workings of the water sector in the Netherlands, and revealing just how resilient it already is! I can almost go back to taking tap water for granted again.

And finally, thank you to my family, friends, roommates, and study friends for the support, reading chapters, giving valuable feedback, helping me with modeling, answering random questions, and for the much-needed distractions. Thank you to Koen, for the continuous love and support, despite all my ups and downs, for taking walks with me, even in the rain, and listening to me rant. Without you, I would have never known what a Weibull curve was!

This was a challenging yet incredibly educational experience. I started not even knowing where drinking water comes from. I am incredibly thankful for all the people who have taught me all I needed to know to write this thesis. I hope you enjoy the read!

Emma van Kleef

Rotterdam, April 2024

Executive Summary

A societal collapse, characterized by the rapid loss of an established level of complexity in a society, is becoming more conceivable. It can be triggered by a multitude of things, but it has been observed in past collapses to be a result of many internal and external factors. A general theory for why societies collapse is because of an unsustainable increase in complexity. In such cases, the costs of maintaining or increasing complexity begin to outweigh the benefits, because of a decrease of the marginal benefits. Quantifying the risk of societal collapse is challenging due to the high level of uncertainty involved. Based on historical observations, the likelihood of societal collapse may have a wide range from rare to likely. Its effects are most certainly catastrophic to existential. Considering societal collapse as a given, this opens the opportunity to investigate ways that infrastructures must become resilient which go beyond the response to short-term disruptions.

The water sector is an interesting case study. It's unique in its components and services. Its criticality is undisputed: in a collapsing society, access to clean drinking water is a high priority. Thus, ensuring that it can be resilient to these pressures can further extend the future-proofness of the infrastructure.

A key vulnerability lies in the sector's interdependencies. For the production of drinking water, several components are required. These components and their usages create a web of dependencies that the water sector is reliant on to effectively abstract, treat, store, and distribute drinking water. Currently, although many efforts are made to increase the resilience of the water sector, regarding its interdependencies, these resilience efforts are limited to short-term disruptions, and not focused on long-term pressures. The main research question, as a result, is:

How might the water sector respond to pressures associated with a societal collapse, given its high interdependencies with other sectors?

The production of water is dependent on many components, but these can be scoped to be from the following sectors:

- Telecommunications & IT Infrastructure: for communication and automated processes at water production facilities.
- Energy sector: for electricity and fuel.
- Chemical industry: for chemicals needed for water treatment.
- Manufacturing industry: for equipment needed at facility locations.
- People: for specialized workers with specific knowledge.
- Financial & banking sector: for long and short-term funding.
- Transportation sector: for the movement of required components; chemicals, workers, materials, etc.

Given this web of dependencies, an exploratory model was created to try and understand how failures can cascade through this network of dependencies, in several possible societal collapse scenarios. By subdividing each sector into interdependent components, a network was created. A link between a component signifies that that component requires another component to function. The disruptions propagate through the network to simulate cascading failures.

The model is affected by forces driven by societal collapse scenarios. This is modeled as a series of curves that represent disruptions to several components. The components that are directly disrupted are: Electricity, Fuel, Telecommunications, Financial and Banking, Chemical, Manufacturing, and Transportation. This is based on plausible consequences of societal collapse. Furthermore, there is a damage multiplier affecting the dependence of the water sector on specialized workers and transportation, and finally, a contamination curve that affects the available clean water for abstraction. These disruptions are modeled using a Weibull distribution curve. This curve encompasses both increasing and decreasing disruption rate functions, which approximates the assumptions regarding societal collapse. In addition to these curves, there is also a change in population in the model, which leads to a change in demand. If

the population migrates out of the system, then a part of the specialized workforce may depart as well, which reduces the performance of that component.

The model relies on a dependency matrix to calculate the response to a societal collapse scenario. These dependencies are difficult to quantify, yet there are several approaches in the literature. In this research, two approaches were used, which were expert interviews, where experts were asked to assign a score of dependence, and economic Input-Output tables. Both of these were tested in the model. The matrix generated based on expert elicitation was compared with a randomly generated matrix. It resulted in significant differences in average performance for the same scenario, which indicated that defining the matrix is integral to obtaining interpretable and usable results. In Input-Output tables, accurately depicting dependencies is difficult because the vast differences in transaction sizes can make smaller values seem insignificant. When normalizing the values to obtain a dependency value, the resulting matrix is very sparse. In the model, this led to more cascading failures, but it also reduced the recovery ability of the components, as having more dependencies can boost the performance of the water sector.

Finally, the effect of adaptation through dynamic dependencies was investigated. The water sector was given three strategies with which to boost its performance.

- **Strategy 1:** using emergency generators removes the dependence on electricity but leads to a high dependence on fuel and transportation.
- **Strategy 2:** completely excluding chemical water treatment removes the dependence on chemicals and reduces the dependence on transportation. This would require accepting a somewhat reduced but still acceptable water quality.
- **Strategy 3:** a combined use of electricity from the network and emergency generators, leading to a lower dependence on electricity and a medium dependence on fuel, with a slightly higher dependence on transportation. This would be relevant in a scenario of long periods of intermittent energy supply.

The use of strategies leads to an improvement in performance for the abstraction and treatment components of the water submodel. In cases where a single component performed worse, it was the result of optimizing for the combined performance of the components.

The model does not entirely represent the interdependent system, nor the effects of a societal collapse. However, it provides insights into tackling the problem of modeling complex interdependent sectors, and how to model a societal collapse. The model serves as a way to query how we are thinking about the problem rather than providing the solutions. It prompts new ways of thinking: should we investigate possible adaptation methods, if these are generally better and less costly than redundancies?

A societal collapse will undoubtedly cause unprecedented disruptions, but understanding how these disruptions affect the water sector might help to make the water sector more resilient. For future research, sector modules could be substituted with more complex domain-specific models. These could replace the transfer functions and give a more realistic calculation of a reduced input leading to a reduced output. The modeler must critically evaluate the return on the modeling effort and consider whether overcomplication might reduce understanding. Simpler models can provide non-trivial insights into the basic mechanisms driving system response to disruptions, whereas more complex and accurate models may obscure the origin of the phenomena.

Contents

Symbols and Abbreviations

Symbols

Symbol	Definition
i	Component i: the component of interest
j	Component j: another component
w_{ij}	Dependency weight from component i on component j
W	The set of w_{ij} for all i for all j
P_i	The performance value of component i
X	The set of components on which component i depends
$\|X\|$	The cardinality of the set X
$g(x)$	A function g which is applied to x
k	The shape factor of the Weibull curve
λ	The scale factor of the Weibull curve
τ	The threshold of the Weibull curve
α	The shape factor of the sigmoid curve
x	The scale factor of the sigmoid curve
P_{pop}	Performance of the Population component
P_{pop}^{t}	Performance of the Population component at time step t
P_{pop}^{t-1}	Performance of the Population component at previous time step, $t-1$
ΔP_{pop}	Difference in performance of Population component over one time step
D_t	Demand at time step t

Abbreviations

Abbreviation	Definition
RO	Reverse Osmosis
CapEx	Capital Expenses
OpEx	Operational Expenses
SD	System Dynamics
EMA	Exploratory Modeling and Analysis
MOP	Measurement of Performance
RMSE	Root Mean Squared Error
MSD	Mean Signed Difference
LHS	Latin Hypercube Sampling
IO	Input-Output

1 | Introduction

"Today the world will end. You never know, we may recover." - Portugal. The Man, So Young.

The drinking water sector is an important critical entity that is unique in its components and services (European Union, 2022). Problems encountered within the sector today require more complex solutions than before. As there is sufficient incentive to address the risk of a potential societal collapse (van Thienen, Chatzistefanou, Makropoulos, & Vamvakeridou-Lyroudia, 2023), it is integral to consider how disruptions caused by this could affect the water sector. The high level of interdependencies between the water sector and other sectors exposes vulnerabilities that could challenge the provision of drinking water during or after a societal collapse.

Critical entities, as providers of essential services, play an indispensable role in the maintenance of vital societal functions or economic activities in the internal market in an increasingly interdependent economy (European Union, 2022). As such, an incapacity to continuously provide drinking water to citizens can have large consequences. A significant aspect of the problem presents itself in the way the sector interacts with other sectors. Cascading failures, where the failure of one system leads to the failure of another, even if the latter isn't directly reliant on the former (URS, 2010), expose a pathway of vulnerabilities throughout the system of systems. Such a pathway can have adverse effects on the ability of the water sector to supply water, which may not be considered when studying the water sector in isolation.

1.1 Societal collapse

In his work A Study of History, Arnold Toynbee said that "great civilizations are not murdered, instead, they take their own lives" (Kemp, 2019). He thereby touches on an important concept, namely that we, as a society, are responsible for causing our own demise. In turn, he also highlights the following: we are also responsible for preventing it. Though societal collapse may be regarded as a thing of the past; where Greek Rulers, Roman Emperors, Egyptian Pharaohs, and Mayan Kings led their society to failure, it is a plausible threat to any society. A conceivable societal downturn threatens our modern world through crisis after crisis, emerging problems from climate change, and a myriad of other pressures.

While climate has historically played a significant role in the fall of civilizations, it is just one of many factors that can cause societal collapse. Research into past collapses, such as that of the Mayan civilization, reveals that while environmental challenges played a part, a complex interplay of internal and external pressures was at work (Kennett et al., 2012; Haug et al., 2003; Kohler & Rockman, 2020).

Today's global societies face an array of threats that, in combination with the stressors of current anthropogenic climate change, could lead to failures. As stated by Kemp (2019), technological advancements do not make us invulnerable to the risks our ancestors faced; rather, they introduce new complexities to our interdependent infrastructures. A multitude of interplaying factors could cause our societies to collapse, aggravated, perhaps, by climate change.

The summer of 2023 in Europe has already shown hints of the detrimental weather patterns that may relate to climate change, ranging from prolonged droughts to mass flooding, heat waves, and hail storms. These weather patterns, along with other consequences of climate change are responsible for much uncertainty for future planning, as future emissions, concentrations, warming, and impacts of climate change are all unknown (Kemp et al., 2022), making studying them and learning to adapt all the more urgent (Peñuelas & Nogué, 2023). In the water sector, where infrastructure built today may survive during a future collapse, we must ensure that a (basic) level of water supply can be maintained (van Thienen et al., 2023).

1.2 The interdependent drinking water sector

Infrastructures have become closely intertwined due to modern technologies and demands, forming a complex system of systems. These interdependencies between systems introduce an additional factor of risk, as failures in different sectors may propagate, causing trickle-down effects that can grow to cascading failures. For example, the water sector is strongly dependent on energy for many of its functions, i.e. the function of water pumps. A long-term loss of electricity leads to reduced functionality of pumps, which may lead to a decrease in the capacity of water utilities to provide water to homes. However, a lack of electricity can also affect sectors on which the water system is dependent, such as IT and Telecommunications, making it impossible to obtain sensor data, thus potentially debilitating effective recovery of the water system. Pressures from a societal collapse could affect either the water system directly or indirectly through a sector on which it may be dependent. Given the complex interplay and mechanisms within a societal collapse scenario, the drinking water supply could be impacted in various ways.

Research on critical infrastructures, such as drinking water, while advancing rapidly in recent years, has yet to consider the effects of societal collapse. There is much uncertainty concerning the occurrence of a societal collapse and the pressures it may exert on critical infrastructures such as the water sector, especially due to the complex ways it interacts with other critical infrastructures and sectors. This research aims to make a start in analyzing how such an interdependent system may respond to sustained pressure, and where its vulnerabilities lie with regards to how it is interconnected. As long-term crises are already putting pressure on our drinking water system, it becomes all the more significant to research its resilience in the case of a societal collapse.

1.3 Knowledge gap and research questions

The water sector's interdependencies come with vulnerabilities and complex interactions that can lead to cascading failures. In the context of societal collapse, understanding the response of the water sector to failures cascading through the interdependent sectors is thus the goal of the research. To effectively analyze the effect that a societal collapse has on the water sector, the water sector must be considered as part of an interconnected web of dependencies.

While much research has been conducted on the implications of interdependencies on the resilience of critical entities to perturbations (Ouyang, 2014; Baylis et al., 2016; Gillette, Fisher, Peerenboom, & Whitfield, 2002), these are mostly focused on the response to single disruptive events. There is a lack of research on the impact of sustained pressures on the system, and how it may be resilient to these stressors. In addition, very little research considers the possibility of finding a new balance after societal collapse and changing dependencies to cope. Acknowledging the literature that finds societal collapse a plausible scenario, it is crucial to investigate the repercussions on critical infrastructures due to a societal collapse. In short: as the threat of societal collapse becomes greater, the water sector as a critical infrastructure should try and increase its resilience in the face of such pressures.

The knowledge gap thus presents itself in considering the influence of a given societal collapse on interdependent critical infrastructures. A societal collapse presents a whole other set of problems than simply a single disruptive event, for which the water sector is already very resilient. Approaching the resilience of interdependent critical infrastructures through the lens of societal collapse offers a novel perspective.

Understanding dependencies and how disruptions propagate through a system is crucial to modeling the effects of a societal collapse, to understand in what ways the sector becomes vulnerable. The challenge lies in modeling the interconnected system to represent this, as well as modeling the effects of a societal collapse without knowing in advance how such a collapse takes shape. Finding an appropriate modeling approach that can help to understand the response and make ascertainments on the effect of societal collapse pressures, given a high level of uncertainty, is the focus of the study, resulting in a proof of concept that could be expanded on in future research.

This leads to the following research question:

How might the water sector respond to pressures associated with a societal collapse, given its high interdependencies with other sectors?

And the following subquestions, which will aid in answering the main research question:

SQ1: What is societal collapse and what are the potential pressures associated with it?

SQ2: What are the sectors that the water sector is dependent on, forming the water sector's web of dependencies?

SQ3: How can the water system and its interdependencies with other sectors be represented effectively?

SQ4: How can the dynamics within and across the interdependent sectors be determined and represented?

SQ5: How can the effects of societal collapse be modeled?

SQ6: How does understanding these responses help to increase the resilience of the water sector to societal collapse?

As it is not possible to predict the future, and given the high uncertainty as to how societal collapse may take place, this research does not consider the possible reasons that may lead to societal collapse but considers societal collapse as a given. Several uncertainties arise from how societal collapse affects the water sector, and these will be investigated. The studied sector is the water sector, and the investigated dependencies will remain limited to only the sectors that are relevant to the water sector's operations. The goal of this research is to investigate how critical infrastructures could benefit from considering the possibility of a societal collapse.

1.4 EPA relevance

This thesis is written to obtain a master's degree in Engineering and Policy Analysis (EPA). EPA is focused on addressing grand challenges, with an inherent technological and social component. A societal collapse presents a multitude of challenges that cover all aspects of the socio-technical system. The water sector in the context of all of its interdependent sectors is addressed as a large complex adaptive system with social, political, and technical elements. The analysis stems from understanding how such a system responds to wide-scale disruptions. The final intent of the larger research project is for decision-makers of infrastructures to acknowledge more extreme scenarios and encourage new forms of resilience thinking that can address those challenges.

The knowledge gap is tackled through the use of modeling techniques that try to simulate cascading failures and model the potential consequences of a societal collapse. These models have the goal to increase understanding and identify elements relevant for future research, to eventually increase understanding and strengthen decision-making.

1.5 Thesis outline

This thesis is divided into seven chapters, with the first serving as the introduction. The subsequent chapter delves into the necessary background information for understanding societal collapse, water production, and the interdependencies within the water sector. The model is then explained in three parts: firstly, through the modeling cycle, beginning with conceptualization and culminating in formalization, with a thorough description of all model elements. Next, the model input, encompassing all elements fed into the model, is detailed. Lastly, the model's application is analyzed through three different experiments to understand how varying inputs influence outcomes. Following this, the results and model outcomes are discussed to determine their applicability to future research. The thesis concludes with a summary of findings and recommendations.

A visual thesis outline is presented in figure 1.1, with the main question that the chapter will answer.

Chapter	Goal	Subquestion addressed
Chapter 1 Introduction	Why was this researched?	
Chapter 2 Background	What is this research about?	SQ1, SQ2
Chapter 3 Model description	How is the model built?	SQ3, SQ4
Chapter 4 Model input	What goes into the model?	SQ5
Chapter 5 Model analysis	How do the inputs affect the outcomes?	
Chapter 6 Discussion	How can we interpret the model?	SQ6
Chapter 6 Conclusion	What can we do with this research?	

Figure 1.1: Report outline

2 | Background

This section will examine the information provided in the introduction, with an elaborate literature review, reflection, and input from the interviews. This chapter strives to clarify the concept of societal collapse, and the current state of research within this field. Next, the application of the case for the drinking water sector will be explained, and the adaptation strategies it may already possess. Then, each identified and relevant sector upon which the water sector is dependent will be expanded on, with information gained from the interviews. Intersectoral dynamics within and across sectors will be explained for each, and finally, the chapter will review the literature regarding the quantification of these dependencies. It will conclude with what relevant information is required for the next chapter.

This chapter will provide insight into subquestion 1: *What is societal collapse and what are the potential pressures associated with it?* and subquestion 2: *What are the sectors that the water sector is dependent on, forming the water sector's web of dependencies?*

2.1 Approach

The approach for consolidating the information presented in this chapter is through a thorough literature review and reinforcement with input gained from expert interviews.

The literature review has two main focuses: Societal Collapse and Interdependent Infrastructures. The deployed search strategy was examining existing literature reviews and using the identified topics and papers to synthesize the relevant research for this problem. Investigating the literature reveals a lot of information on what is currently known and unknown about both topics and gives a good basis with which to conduct interviews.

The interviews were conducted to answer SQ2, SQ3, and SQ4. The interviews were semi-structured, including specific questions with the flexibility to ask unplanned follow-up questions and discuss them in any order, using both open and closed questions. This method of interviewing is the most common qualitative research method (Qu & Dumay, 2011). It encourages interaction with the interviewee and is beneficial when investigating complex issues, as respondents can express their ideas in a more unrestricted way (Johannesson & Perjons, 2014).

The interviews help to understand the real-life experienced interdependencies in the water sector and to give an idea of the awareness of these interdependencies by those working in the water sector. The interviewees were asked to describe their mental model of the interdependencies and rate each sector according to its importance to the water sector. The interviewees were also asked to recall an example of disruptions that affected their daily operations, to allow them to mention how the water sector responds to disruptions. An overview of the questions asked is provided in appendix A.

To gain a broad perspective, a range of experts from different drinking water companies with different levels of operation were chosen. Table 2.1 shows the interviewees, their organization, and their role within the organization. To refer to interviews in text, reference codes are used, which are mentioned in the last column.

Role	**Level**	**Water company**	**Reference code**
Strategic advisor sustainability	Strategic	PWN	(PWN1)
Advisor crisis management	Strategic	Waterbedrijf Groningen	(WBG1)
Asset management	Management	Vitens	(VIT1)
Innovation manager	Management	Vitens	(VIT2)
Process controller	Operational	Vitens	(VIT3)
Process operator	Operational	Vitens	(VIT4)
Process operator	Operational	Oasen	(OAS1)

Table 2.1: Conducted interviews and their reference codes

The information gained from the interviews was transcribed, summarized, and coded using ATLAS.ti, a useful software for encoding and analyzing qualitative data (Qu & Dumay, 2011).

2.2 Societal collapse

As the water sector faces the implication of a societal collapse, it is essential to consider how the effects of such a collapse may affect its resilience. The focus lies in the investigation of how the interdependent systems, as well as the water sector, respond to sustained pressures from a societal collapse.

Societal collapse is defined in many ways. It is a difficult concept that defies a strict definition, mostly as a result of the multitude of ways it may emerge (Lawler, 2010). Joseph Tainter (1988), renowned for his influential work "The Collapse of Complex Societies," provides a comprehensive analysis of the factors leading to the fall of advanced civilizations. In his words, a societal collapse can be seen as the rapid loss of an established level of complexity of a society, which is the result of a decrease in marginal benefit due to the complexity (Tainter, 1988). Collapse causes society to return to a much more rudimentary form of civilization. Whether as a cause or as a consequence, it is accompanied by a marked, rapid reduction in population size and density (Tainter, 1988). Kemp et al. (2022) expands this definition as: "[a] significant sociopolitical fragmentation and/or state failure along with the rapid, enduring, and significant loss [of] capital, and systems identity; this can lead to large-scale increases in mortality and morbidity."

Richards, Lupton, and Allwood (2021) find that collapse may be rapid, taking no more than a few decades, and experienced by a local, national, or global community of people. Cumming and Peterson (2017) state that collapse must be substantial compared with previous system fluctuations; persistent, without quick recovery; and abrupt, not a slow decline. The loss of political identity can be a consequence of societal collapse, which means that political institutions as we have them today may cease to exist. There are also cases where there is continued political identity, but a loss of political control. This is also considered a societal collapse.

2.2.1 Conceivable societal collapse

Societal collapse is driven by a multitude of factors, and it is often the interplay between internal and external factors that lead to societal collapse (Tainter, 2022). Historical cases of societal collapse have been largely researched by different disciplines (i.e. archaeology, statistics, and history) and clarifications for societal collapse are tenfold (Tainter, 2022). Collapse is not the same for each society and its drivers and responses are inherently complicated and difficult to predict (Brozović, 2023). Cumming and Peterson (2017) identify 14 distinct mechanisms that may lead to a collapse in socio-ecological systems. These are closely related to the initial structure of a society and consider the various ways a society may collapse with a variety of different causes. Cumming and Peterson (2017) believe that the loss of complexity does not necessarily imply collapse; systems may still reorganize in ways that reduce complexity while maintaining identity. A society may even simplify to avoid a collapse.

In the literature, climate change is attributed as an important cause for past collapses (Weiss & Bradley, 2001; deMenocal, 2001), but Tainter (2022) finds that there are many internal factors besides such external factors that contribute to collapse. However, the identification of abrupt climactic problems is not to be disregarded, as many papers have identified a positive correlation (Haug et al., 2003; Hodell, Curtis, & Brenner, 1995; Medina-Elizalde & Rohling, 2012). In the paper by Richards et al. (2021), several factors were determined that may directly affect human mortality, such as shifts in average weather and natural hazards. Both effects, coupled with rising sea levels could lead to a degradation of the natural world system and thus the human world system, leading to resource and service insecurity (Richards et al., 2021).

Despite the many different drivers for a societal collapse, the complexity theory has emerged as one of the most compact general theories of collapse (Brozović, 2023). As systems develop, they begin to experience diminishing marginal returns to growth; it creates problems whose solution requires more complexity (Hanson, 2007). Eventually, the cost of adding complexity is too high for the problems it tries to solve, and the system collapses, reorganizing in a simplified state (Cumming & Peterson, 2017).

A compelling argument for a conceivable societal collapse is the transgression of planetary boundaries. Rockström et al. (2009) proposed the concept of planetary boundaries within which humanity can operate safely. Transgressing one or more boundaries may lead to catastrophic consequences, leading to non-linear, abrupt environmental change, often irrevocable. The most recent update by Richardson et al. (2023) has found that six of the nine boundaries have already been transgressed, suggesting that

Earth is now well outside of the safe operating space for humanity. Pressures from this transgression impact the availability and distribution of food production, the availability of water, vector-borne diseases, and extreme weather, which is known to have led to past societal collapse (van Thienen et al., 2023). The transgression of planetary boundaries introduces chaos into the Earth's system, where sensitive dependencies in initial conditions can lead to unpredictable and potentially catastrophic consequences. As humanity exceeds safe operating limits, the future trajectory of environmental change becomes increasingly uncertain, highlighting the nonlinear dynamics and complex behavior inherent in the interactions between human activity and the Earth's systems.

Risk of societal collapse

Kemp et al. (2022) argue that these trends could have catastrophic consequences, and understanding extreme risks is crucial for future decision-making and emergency response preparation (van Thienen et al., 2023). When considering the risk of societal collapse, we can plot it in the risk matrix as shown in figure 2.1. This matrix shows the risk as a product of (estimated) likelihood and impact. van Thienen et al. (2023) propose an extra column "Existential impact" to quantify the risk of a societal collapse, although much uncertainty exists on the likelihood of a collapse.

	Negligible	Minor	Moderate	Major	**Catastrophic**	**Existential**
Almost certain	Moderate	High	Extreme	Extreme	Extreme	Extreme
Likely	Moderate	High	High	Extreme	Extreme	Extreme
Possible	Low	Moderate	High	High	Extreme	Extreme
Unlikely	Low	Moderate	Moderate	High	High	High
Rare	Low	Low	Low	Moderate	Moderate	Moderate

Figure 2.1: Risk matrix societal collapse (van Thienen et al., 2023)

We do not have the means to quantify the likelihood of a societal collapse, but given the abundance of historical precedents, it cannot be considered to be rare or unlikely. Hence, it is possible, or, according to Bologna and Aquino (2020), likely. Thus, the effect of societal collapse is extreme and should be considered for future planning, due to the high impact it will likely have on the affected sectors.

It is important to differentiate societal collapse from human extinction. A societal collapse only considers the collapse of an established society, accompanied by increases in mortality, which does not imply human extinction. After a collapse, societies can recover, rebuild, or transform into new forms. Although Kemp et al. (2022) consider collapse and existential risk of humanity closely bounded, especially when caused by extreme climate change, other authors argue that to a societal collapse, reorganization and recovery is inherent (Tainter, 1988; Schwartz & Nichols, 2006; Brozović, 2023; Taleb, 2007). In this thesis, societal collapse is only considered as the definition that entails a loss of complexity in a society, leading to more severe disruptions than the disruptions that may have caused the collapse (Hanson, 2007), with adaptation capabilities that can foster a recovery (Schwartz & Nichols, 2006).

2.2.2 Collapse phases

Though most papers consider the period heading toward a societal collapse, there aren't many regarding a period after or during the collapse. This research will assume mechanisms that cause a societal collapse have already taken place, and the system in focus operates during or post-societal collapse. Tainter (1988) sees the aftermath of collapse as a transitional period, where the population can no longer rely on external defenses and internal orders, including the continuation of required goods being delivered. Post-collapse, societies can reorganize and rebuild, often in a simpler, less complex form. In the book After Collapse by Schwartz and Nichols (2006), the authors note that collapse is seldom total or complete and that regeneration consists of the reconstruction of the same kinds of institutions and phenomena that existed before the collapse. The regeneration takes form in the reappearance of societal complexity after periods of decentralization, not the reappearance of the specific complex society that collapsed

(Schwartz & Nichols, 2006). To contextualize societal collapse for this research, figure 2.2, adapted from Cumming and Peterson (2017) and Tainter (1988), and the ideas from Schwartz and Nichols (2006), shows how complexity over time may evolve.

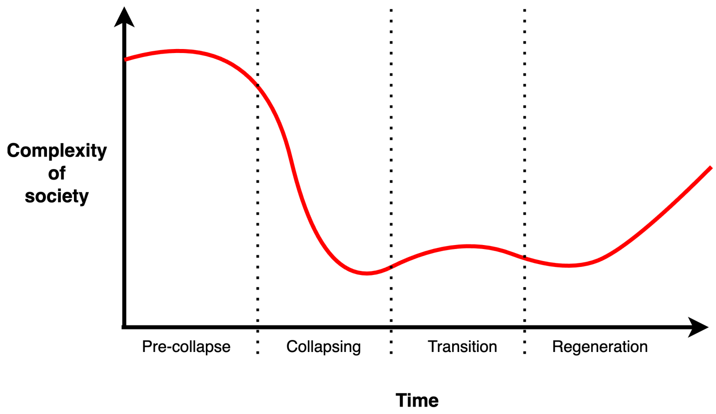


Figure 2.2: Phases of societal collapse

This research focuses on the collapsing and transition phases because these are the periods when society faces the most pressure from societal collapse, and has the lowest level of complexity.

2.2.3 Sustained pressure after societal collapse

In the aftermath of a societal collapse, consequences that hinder the continuation of water supply are expressed in the following 8 scenario elements by van Thienen et al. (2023). The elements, in combination with each other and at different levels, can become plausible scenarios for post-societal collapse pressures. The effects can be the result of societal collapse, but can also be caused by an interplay of all the internal and external effects that lead to a societal collapse in the first place. Each is directly obtained from the paper by van Thienen et al. (2023), which are partially based on Bolton (2020).

1. Sharp increase or decrease in water demand from displaced people: climate refugees towards or away from the Netherlands due to extreme weather, sea level rise, or social decline.
2. Departure of qualified (technical) personnel: due to similar processes as above.
3. Physical damage to infrastructure: collateral damage or deliberate sabotage or theft.
4. Reduced availability of electricity: due to similar processes.
5. Erosion of the financial sustainability of water companies: increased non-payment and/or water theft; (partial) failure of the financial system.
6. Reduced availability of (high-tech) components and chemicals: decline in production, transport, trade, and financial services, partly through similar processes.
7. (Partial) breakdown of data and communication infrastructure: partly through similar processes.
8. Contamination of sources: by reduced security or containment of chemical or nuclear products or waste materials through similar processes, that may consequently spread via water or wind.

The above narratives can help to ascertain what kinds of pressures are exerted on the water sector and how they might affect the system. This is a start in answering subquestion 1. To scope the problem, the above 8 elements will be the only consequences of societal collapse to be explored in this research.

2.3 Drinking water

The water sector is reliant on many different streams of input to produce clean drinking water and distribute this through pipelines to various consumers. This reliance on inputs makes the water sector the center of a complex web of dependencies, that are situation-dependent and critical in different scenarios. When considering a plausible societal collapse, one of life's basic necessities is water, and people will need it to survive. In the world we live in today, water in lakes and rivers is not as readily drinkable as they were for early settlers. Instead, production facilities with high security and complicated machinery are required to produce the drinking water. Their reliance on so many sectors makes them very vulnerable to stop functioning, aggravating potential pressures exerted on the population during a societal collapse.

To understand what these dependencies are, it is important to consider what part of the process is being considered, and what kinds of inputs are required. This will be elaborated on in this section, as well as examples of robustness and resilience measures already in place.

2.3.1 Drinking water production

Drinking water in the Netherlands is mainly sourced from groundwater, due to the high quality and hygiene of the water (VIT1). The source of that water is mostly from mid to east Netherlands, as the west side of the country's groundwater is often brackish (Noordhoff, 2021). Other methods include extraction of groundwater from riverbanks, surface water, or infiltrated water, where water is obtained from surface water or similar locations and deposited into natural areas for natural filtration (Noordhoff, 2021). Each process type has its own selection of dependencies, and within each process type, there are different quantities and types of inputs required for treating the water. To explain, in broad terms, how water is produced, figure 2.3 shows a schematic rendition of the process.

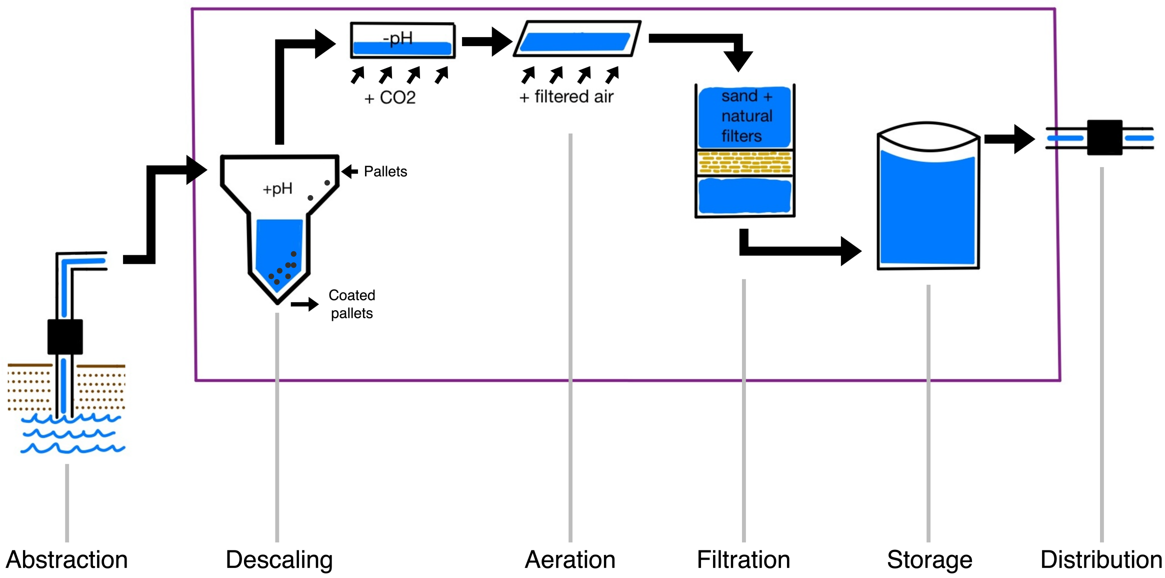


Figure 2.3: Water production process (VIT4)

For groundwater abstraction, the steps for treatment include descaling, aeration, and filtration. To descale the water, the pH is increased, so that the calcium forms solids. Pallets made of grit material are added to which the calcium binds, which become heavier and sink to the bottom of the tank (Bos & Merks, 2000). These pallets are then removed and stored for collection by transport. To increase the pH, various chemicals can be chosen, which are often selected based on the properties of the groundwater, depending on the concentration of calcium and other minerals that may need to be removed (Pujiastuti, Ngatilah, Sumada, & Muljani, 2018). These can be sodium hydroxide, calcium hydroxide or sodium carbonate, which lead to a chemical reaction that is favorable for the removal of calcium (VIT4). Afterward, to decrease the pH, CO_2 is added (VIT4).

After the descaling process, water is aerated to oxidize the iron and manganese, which is then captured in the filters (VIT4). This can be done through, for example, diffusers on a plate where the body of water lies where high volumes of air are blasted through, causing bubbles (VIT4). A second example is through the use of fine sprinklers which allow the water to mix with the surrounding air (VIT4). The filters contain anthracite and 1,5 m of fine gravel, which additionally capture any of the carry-over from the softening process (VIT4). After this, treatment ends and enters the storage tanks, after which the water is pumped through to the distribution network.

2.3.2 Resilience of the water sector

Resilience is a dynamic, multi-faceted term that has many definitions (Nan, Sansavini, Kröger, & Heinimann, 2014). It contains several subfactors that can help to improve resilience. Among those are robustness, redundancy, resourcefulness, and rapidity (Tierney & Bruneau, 2007). In the paper by Nan et al. (2014), resilience is seen as the ability of a system to withstand a disruptive event by reducing the negative impacts, adapting itself to them, and recovering from them. These can be categorized into three main capacities, absorptive, adaptive, and restorative capacity, as shown in figure 2.4. Robustness, defined as the strength of the system to resist disruptions, is an example of the absorptive capacity of a system (Bruneau et al., 2003). Increasing the redundancies of a system is a way to increase resilience (Nan et al., 2014). When considering adaptive capacity, Nan et al. (2014) refer to the endogenous ability of a system to adapt to disruptions, through self-organization. This dynamic ability of a system can be enhanced through the changing of operations in such a way that critical functionality is sustained. Lastly, restorative capacity refers to the exogenous ability of a system to be repaired for recovery (Nan et al., 2014). This refers specifically to repairing damage to systems that cause disruptions.

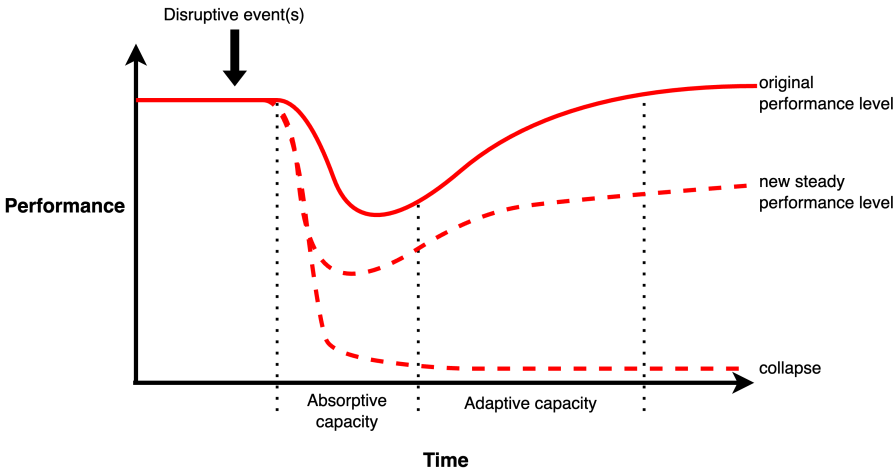


Figure 2.4: Resilience capabilities, adapted from Nan et al. (2014)

The concept of resilience has gained a lot of attention over the past years, as many hazardous events have highlighted the need to increase the resilience of our cities, infrastructures, ecosystems, etc. in the face of hazards. Most studies are centered on the ability to rapidly recover and "bounce back" to the original state (IPCC, 2023). In the paper by Champlin, Sirenko, and Comes (2023), they indicate that COVID-19, along with heatwaves, floods, earthquakes, and other shocks that compound, require a newer form of resilience. The IPCC proposes a newer definition in relation to climate resilience, being "the capacity of social, economic and ecosystems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity, and structure" (IPCC, 2023). The mention of "trend" proposes that resilience is also of importance when considering long term pressures. In the glossary by Mentges, Halekotte, Schneider, Demmer, and Lichte (2023), a "slow-onset disruptive event" is a similarly suitable description for societal collapse pressure "trends", as a disruptive event whose intensity increases over a longer period. "Responding or reorganizing" is the possibility for a new state to exist, which requires reorganization, but still maintains the essential function, identity, and structure. For the water sector, these elements require infrastructure that can continue to deliver water reliably and can be maintained effectively.

In the face of disruptions, resilience is of utmost importance for critical infrastructures such as water. As stated by Dueñas-Osorio and Vemuru (2009), the demands for flow through these critical infrastructures are growing at a rate that outpaces the efforts to upgrade the capacity, and disruptions (also from other systems) can lead to cascading failures, impacting the performance.

The importance of the water sector is recognized in the Netherlands as the water infrastructure pertains to category A of critical infrastructures, where any disruption, degradation, or loss will lead to at least one of the following consequences: approximately 50 billion euros in damage or a 5% drop in real income, more than 10,000 dead, seriously injured or chronically ill, more than 1 million persons experiencing emotional distress or serious problems with basic survival, and cascading effects in at least two other sectors (National Coordinator for Counterterrorism and Security, 2023). A societal collapse exerting pressures in the form of the above-mentioned mechanisms can lead to a serious disruption of the water system, resulting in an incapacity of the water sector to meet its demand. In the EU directive 2022/2557 drinking water is listed as a critical entity, and ensuring its resilience is an important topic (European Union, 2022).

2.3.3 Adaptation strategies

As mentioned in the paper by Nan et al. (2014), adaptive capacity is an important factor in increasing resilience. For the water sector, the ability to adapt can allow for water to still be produced and delivered in the face of long-term disruptions or disruptive trends. Such adaptations can relate specifically to the mitigation of several dependencies, but also to increase the resilience of the water sector in the face of any kind of risk.

An example from Giuliani, Anghileri, Castelletti, Vu, and Soncini-Sessa (2016) is expanding storage capabilities. They studied the role of large storage operations as flexible means of adaptation to climate change. They considered the risk of failure from other sectors and found that flexibility in large storage can help to mitigate failures (Giuliani et al., 2016). Petersen and Wieltschnig (2020) find an increase in resilience through the implementation of more smart data and pollution sensors. The increase in understanding and being able to mitigate risks from climate issues, however, comes with the risk of having more dependencies (Petersen & Wieltschnig, 2020). Chakrabarti, Hertz, Kabisch, Reil, and Wolf (2015) investigated in India how changing climate causing challenges for the water sector, such as the increasing temperature and changing rainfall patterns relating to alterations in the monsoon trend. They find adaptation techniques by exploring the diversification of the water source options, considering surface water and groundwater, the use of desalination techniques, and improved methods of wastewater treatment (Chakrabarti et al., 2015).

In the Netherlands, Reverse Osmosis (RO) filtration is an example of adaptation from the water sector. RO is a water treatment technology that can remove a large majority of contaminants from water by pushing the water under pressure through a semi-permeable membrane (Puretec, 2023). It does not require any chemicals for treatment, only beneficial minerals are added to the water (OAS1).

It has been proven to be effective in removing micro-pollutants in natural drinking water sources, making it adaptive to contamination (Albergamo et al., 2019) and also many other pollutants caused by anthropogenic activities (Albergamo et al., 2020). It is also able to remove PFAS, PFOA, and Gen-X from river sources (OAS1). It is effective in treating brackish water, a result of salination, as well (Hosseinipour, Harris, El Nazer, Mohamed, & Davies, 2023).

Although RO-filtration presents many advantages, the downside is that it requires an entirely new installation for water treatment, which is expensive (Hosseinipour et al., 2023). The investment in RO facilities is momentarily unnecessary for many water companies that rely on groundwater in the east of the Netherlands as there is currently no big issue of salination and contamination in those sources, however, these might become more relevant in the future. In addition, RO-filtration is known to consume high amounts of energy for effective desalination (Kim, Park, Yang, & Hong, 2019; Patel, Biesheuvel, & Elimelech, 2021). Also, RO-filtration results in a relatively large waste stream, known as brine or RO reject (Yasa ET., 2022). These are directly discharged to sewage systems, ultimately reaching wastewater treatment facilities (OAS1).

2.4 Web of dependencies

Engineered infrastructure systems have witnessed growing integration and interconnectedness, which makes them complex systems (Kröger & Nan, 2014). Any infrastructure is a complex, highly nonlinear, geographically dispersed cluster of systems, each one interacting with the others and with their human owners, operators, and users (Setola & De Porcellinis, 2008). Yet these infrastructures do not exist in isolation from one another, and the interdependencies need to be identified to be able to perform realistic analyses of these (Rinaldi, 2004). The focus of the research on critical infrastructures must then be shifted from single, isolated systems to multiple, interconnected, mutually dependent systems (Zio & Sansavini, 2011).

To analyze the effects of a collapsing society on the water sector, it is important to identify all other sectors on which water is dependent. The water sector, as with many other sectors, is highly dependent on services from other critical infrastructures. This high dependence carries some risks, especially in the face of societal collapse. It is important to note that despite these risks, beneficial effects or opportunities also arise, through asset sharing, knowledge exchange, and/or reorganization capabilities (Grafius, Varga, & Jude, 2020).

An interdependent infrastructure is said to have a bidirectional relationship of dependence which can take multiple forms (Rinaldi, Peerenboom, & Kelly, 2001). Rinaldi et al. (2001) identifies several types of interdependencies, such as physical, cyber, geographic, and logical. Although historically independently managed, modern technology has led to infrastructures becoming more and more complexly intertwined. If we look at infrastructures in isolation, we end up marginalizing the system of systems that may exist around them (Ouyang, 2014). Interdependencies have shown that cascading failures can occur along the chain of dependencies, leading to effects that are not directly related, but rather related through another sector (Ouyang, 2014). In the exercise of identifying these interdependencies, what results is a web surrounding the water sector that demonstrates which sectors are directly or indirectly connected to the water sector, or other sectors. This "web of dependencies", specific to the water sector, can show how pathways may exist. To create this web, it is important to consider a concise set of sectors that are relevant to the water sector and investigate how breakdowns in any of these sectors might affect the ability to meet water demands.

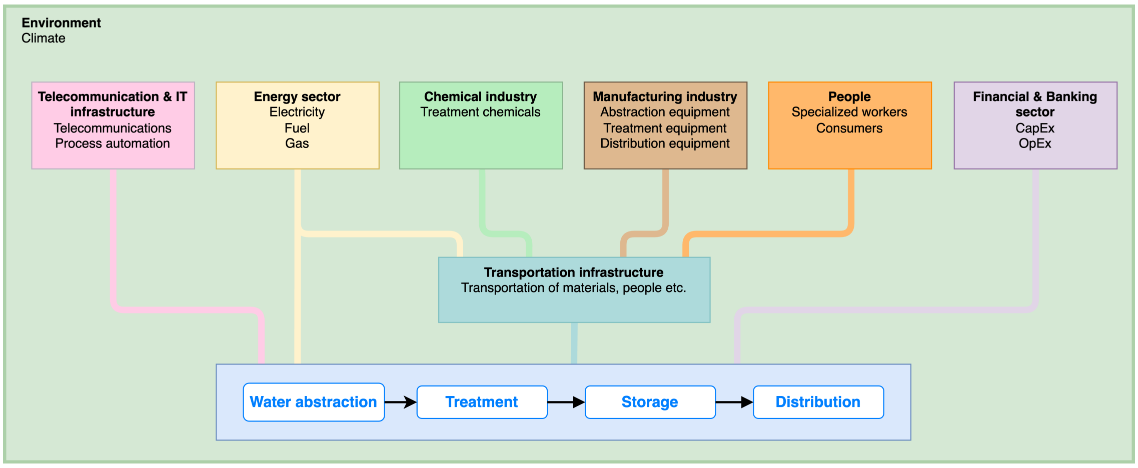


Figure 2.5: Dependent sectors adapted from van Thienen et al. (2023).

In figure 2.5, several sectors are shown on which the water sector is dependent. While the set of sectors identified may not be comprehensive, they can be considered highly relevant and potentially more significant than other sectors. In addition, all 7 interviewees stated that this list of sectors covers all important and relevant dependencies. The following sections will discuss each of the depicted sectors and the way that the water sector may be dependent on these.

2.4.1 Environment

It is important to consider the effects of the environment. As well as affecting many of the other sectors, it directly affects water availability and quality. In the newly published climate scenarios by KNMI (2023), future planning should consider the likelihood of sea level rise, an increase in average temperature, drier summers and wetter winters.

The Intergovernmental Panel on Climate Change (IPCC) reports indicate that more than 87% of climate change effects will impact water infrastructures (Mishra, Kumar, Saraswat, Chakraborty, & Gautam, 2021). The direct effects relate to water quantity, quality, and demand. Water quantity is impacted by increased winter rainfall and extended summer droughts. Water quality is related to increasing sea levels causing salination of groundwater, as there are lower river discharges and an increase in seepage (Phernambucq, Mondeel, van Loon, & Rengers, 2019; URS, 2010). Also, the effect of spills from sewage water treatment plants is much higher due to less dilution of polluting substances (Wuijts, van der Grinten, Meijers, Bak-Eijsberg, & Zwolsman, 2013). The pollutants become more concentrated because of the decrease in water levels. This is especially worrisome for water companies that base their water abstraction on rivers or lakes. Increasing pollutants in this water mean a higher dependence on chemicals for treatment. This is already noticeable with the increase of PFAS in water sources, requiring more treatment steps.

An increase in temperature also means that surface water and groundwater temperature may exceed the limit of 25 degrees for the preparation and distribution of drinking water (Phernambucq et al., 2019).

2.4.2 Telecommunication & IT infrastructure

Interconnectedness is highly facilitated by the IT infrastructure, allowing for communicating objects and continuous information exchange (Gillette et al., 2002). It, however, makes our infrastructures vulnerable in ways that had never been before (Gillette et al., 2002). The water sector specifically has undergone many automation and remote operation innovations in recent years (Baylis et al., 2016). Its reliability on IT infrastructures is evident in its operations and control systems, monitoring systems, internal communications, etc. (Baylis et al., 2016). In the Netherlands, many of the drinking water processes are fully automated or supported by increasingly advanced technology, with a lack of fall-back options or analog alternatives (Phernambucq et al., 2019). The IT infrastructures control the monitoring of water quality, distribution, and customer interfaces control, and in addition, the connections between water and other sectors, such as information on chemical deliveries for inventory (Zimmerman, 2009). IT therefore plays a very large role in facilitating interdependencies between various sectors. In the event of a disruption, either of the power infrastructure or the IT & telecommunications themselves, the high complexity and connectivity of the IT landscape within the water sector, can put pressure on the resilience of the water sector (Phernambucq et al., 2019).

Additionally, in the event of a (data) blackout, it's crucial to acknowledge that many archives, vital information, and databases are typically stored in data centers, which may become inaccessible (VIT1). This further challenges the operations in case of a loss of data, as crucial information needed for operations and decision-making may be unavailable.

Process automation

At water production facilities, Programmable Logic Controllers (PLCs) ensure automatic control of the machines, the entire process runs on feedback loops and sensors (VIT3). These PLCs are connected to an internal internet structure but also the wider web (WBG1). These tend to be redundantly implemented so that if a single PLC system malfunctions, the backup PLC can take over until the main PLC is repaired or replaced (OAS1).

There are three discernible levels of process automation at production facilities (VIT1). The first is the normal situation, where all connections and automation are running, and staff can remotely monitor this. The second is a situation where PLCs are still functioning, but monitoring is not possible, so staff are required to watch the systems. The third is the inability of the processes to run automatically, which requires emergency human intervention (VIT2). A facility that is running in the third format is not likely to be able to maintain its processes for long, as it requires 24/7 monitoring, and the staff cannot maintain such operations in the long term (VIT1).

Telecommunications

Telecommunications in particular refer to all processes that require a phone connection or internet. Water companies have contracts with multiple telecommunication providers that have separate networks so they can easily switch to another network, in case of disruptions (WBG1). This connection is needed for production facilities to regulate pressure by coordinating with others in the network. This communication travels through internet cables but also through telecommunications or radio waves (VIT2). In addition, staff at production facilities, and those on-call, are often assigned to multiple facilities. If there is no possibility of an internet connection to the production facility, staff need to be at the location to monitor the screens on the machines directly (OAS1). If there are issues in the system, another vulnerability forms as a result of outsourcing the IT infrastructure in place at these facilities, as disruptions or errors within these systems are often not understood and mechanics from those companies need to be contacted to be able to fix these (VIT3). If these mechanics can't be reached, it may result in the systems not being fixed.

Efficient crisis coordination relies heavily upon the ability to communicate, and thus a high dependency on telecommunications. There are protocols in place, such as the connection to the emergency communication system, which is a separately connected infrastructure that can be prioritized in a crisis (Kronieger, 2013). There is also the use of portable radio communication if communication is required between locations that are within range (VIT2). These might as well be affected by telecommunication blackouts, however.

2.4.3 Energy sector

The energy sector and the water sector are closely interlinked. Through functional interdependencies, the loss of power will greatly affect the water system. They rely on electricity to operate their pumps, treatment facilities, and pipeline network (Baylis et al., 2016; Balakrishnan & Cassottana, 2022). In other words, the transportation of water is dependent on energy unless transport occurs via gravity (Zimmerman, 2009). The Netherlands being a flat country, water always requires electrical pumping (VIT3). If there is no power, all functionality ends, and water will not be able to be pumped into the system. As water sources close to the city become more and more depleted, water needs to be accessed from greater distances, requiring even more electricity. Currently, most of the water extraction areas are located in the central and eastern parts of the Netherlands, except for some coastal dune areas and surface water abstraction (Noordhoff, 2021). This means power is required to transport all the water from these locations west, which is the more densely populated area of the Netherlands (Noordhoff, 2021). Maintaining pressure in the distribution network in daily operations requires all pumping facilities to operate (Kloosterman, 2020). As a result, extended power disruptions can strain a water utility's alternative energy sources and exhaust fuel reserves, with the situation exacerbated during widespread outages when multiple energy and water utilities have to compete for limited backup resources (Baylis et al., 2016).

Electricity

The burden of having emergency generators falls on the sector that requires it. In the national crisis plan regarding electricity shortages, the energy sector is not required to deliver emergency power, which is different from the requirement of drinking water companies to provide emergency water in crisis (Ministerie van Economische Zaken en Klimaat, 2022). Sectors that rely on electricity for their operations should ensure their own emergency energy reserve.

The need for electricity is central to the operations of the water production facilities. These are required for the pumping of water but also treatment techniques. Functional redundancies exist for cases where there are power outages, such as emergency generators that can keep some pumps active, allowing for continued distribution to most cities. And if there are no emergency generators, then production facilities can be covered by neighboring facilities, through ring pipelines connected to multiple pumping stations (VIT1). This is another form of redundancy, where the maximum capacity of pumping stations with emergency generators can meet water demand. However, this is not a permanent solution, as the neighboring pumping stations are not designed to run at full capacity for an extended period of time, as it can cause pumps to wear out more quickly, and sources to deplete faster (VIT4). The process of switching to emergency generators is also regulated automatically, through built-in voltage detectors (VIT1).

Climate change mitigation efforts significantly impact the energy sector (URS, 2010), which, in turn, influences the water sector. These efforts can lead to increased net congestion, necessitating the upgrading of underground cables to a higher capacity. These cables are frequently installed alongside water and gas pipelines for efficiency, creating a geographical dependency (Rinaldi et al., 2001). When the ground is opened for cable replacement, municipalities prefer to minimize near-future excavations. Consequently, water companies are forced to decide on replacing or repairing pipelines that may not yet require it (VIT1), highlighting the interconnected challenges faced by the water sector.

In line with the energy transition, some water companies want to move from emergency generators to batteries, or other energy storage techniques, to ensure that emergency power is emission-free (VIT2), and to eliminate the dependency on gas or oil. These batteries would also be used to store cheaper or greener energy and self-produced electricity, and can be utilized during periods of high electricity prices or when self-generated electricity production is low (PWN1). The disadvantage of this method is that it still relies on grid electricity to recharge depleted batteries during emergencies, unlike fuel, which might remain accessible, thereby shifting the dependency.

Fuel

The dependency on fuel is inherent to the dependency on electricity. In operations where electricity is continuously available at full capacity, there is no dependency on fuel. With the exception of the fuel required for transportation, the only process that requires fuel is the backup power with emergency generators. To consider the dependency on fuel is to consider a scenario where there is no electricity.

Fuel reserves designated for emergency generators are stored within heated environments to ensure immediate use, eliminating any delay in transitioning from electricity to generator power (VIT2). The fuel reserves at the facilities are enough to power that location at maximum capacity for 10 days, as is determined by law (Drinkwaterbesluit, 2011). Drinking water is placed in category A of the national crisis plan in case of oil shortages, entailing that it will be prioritized in case of a shortage (Ministerie van Economische Zaken en Klimaat, 2023). This is especially relevant in cases where a shortage is combined with a national power outage (WBG1).

Gas

In the case of gas supply, water production facilities are only reliant on this for heating rooms and offices. In addition to the geographic dependence on electricity power lines in the ground, water pipelines are often built close to gas pipelines, leading to this additional dependence (Rinaldi et al., 2001). In addition, some locations have emergency generators powered by gas, a choice stemming from historical instances where water supply and gas supply were managed by the same utility companies (VIT1). Opting for gas-run generators enabled them to be self-sufficient. As gas companies split from water utilities, these generators were not replaced (VIT1). Despite this, there is no critical dependency on gas for production facilities to produce clean drinking water, as heating is not a priority for the production of drinking water.

Despite gas not being a critical component for water production, water demand is highly dependent on gas (VIT1). A loss of gas means a loss of the ability to heat water and thus heat homes, as 90% of homes in the Netherlands use gas for primary heating source (CBS, 2023). This can lead to a decrease in water demand, as there is no possibility of heating water for showers.

2.4.4 Chemical industry

The chemical industry is an important source of dependence at the water treatment level. Water treatment requires a variety of chemicals, in the Netherlands specifically for descaling and filtering, which ensures good water quality and produces safe drinking water. Drinking water systems constantly rely on the supply of these treatment chemicals to maintain their operations, and any interruptions to this supply can have a significant impact on the provision of safe drinking water (Bressman, Brown-Rosenbladt, Edwards, & McGhee, 2022). This dependence however is closely linked to the transportation sector as well, as these are required to deliver the needed chemicals.

In addition, the complex supply chain of chemicals is also relevant. Its complexity lies in the production process of certain chemicals. Often byproducts for the production of an entirely different chemical are used in water treatment, and thus, a change in demand for that chemical decreases the production of its byproducts (Bressman et al., 2022).

Treatment chemicals

In the Netherlands, neither groundwater nor surface water is chlorinated for disinfection. This is due to the high quality of the available water. Chlorine is often used in other countries to disinfect water from parasites, bacteria, and viruses (Centers for Disease Control and Prevention, 2020) and also to prevent the formation of trihalomethanes in PVC pipelines. Furthermore, groundwater treatment does not require a lot of chemicals, compared to other sources, because of the high quality and hygienic reliability of the groundwater (VIT1). The chemicals used are mostly to descale the water.

In general, due to the high quality of the groundwater, a lot of chemicals are only required for pure drinking water. When considering the dependence on chemicals for the production of pure drinking water, this dependence is high. However, in the Drinkwaterbesluit (2011), there are 4 levels of water quality that all drinking water should adhere to. The most important is Table I, which considers microbiological parameters. These must all be kept at zero, and any presence of this material could be threatening to public health (Drinkwaterbesluit, 2011). In the case of groundwater, eliminating the process of descaling and water treatment is still adhering to the requirements of Table I (VIT1). In general, all groundwater treatment processes can continue without the addition of chemicals, and water, though with a higher calcium presence, is still drinkable, it may affect the taste (OAS1). This reduces the dependence on chemicals for specifically water treatment. In addition, many production facilities have a significant amount of chemicals in storage in cases of short-term disruption (VIT2). Another tactic is to use multiple methods of water treatment, each using different chemicals (PWN1).

The reliance on chemicals is significantly influenced by the quality of the abstracted water. For groundwater in the Netherlands, this is not such an issue, except for the high calcium prevalence. For other water sources, a dependence on the chemical industry to adhere to the *drinkwaterbesluit*, chemicals are required.

2.4.5 Manufacturing industry

The water sector is dependent on the manufacturing industry for its pipes and other related components required for abstraction, treatment, and distribution (Baylis et al., 2016). The water sector also relies on the durability of these components, expecting that they are built to last, and are robust to certain environmental changes.

Generally, for all processes, preventative replacement of equipment at treatment facilities is not commonly practiced (VIT3). This is because replacing these high-tech parts is very expensive, and given that parts are often redundantly available, the reserve parts can take over the work until the broken part is replaced (VIT2). Also, the replacement is often a result of energy deficiency, as opposed to being damaged (VIT1).

Some parts are standard sizes and components that can be easily obtained from multiple suppliers (OAS1). Not all parts, however, are always readily available, as idle supply is not cost-effective (VIT3). Due to long lead times, parts need to be ordered well in advance, and some predictive models or thresholds can be used to determine when a part is due for replacement (VIT2). This has multiple benefits, as parts can be ordered on time and planning can be done well ahead, instead of only responding when parts are broken and dealing with a reduction in capacity (VIT2).

In recent times, however, the chip shortages have caused production issues for critical PLCs and other systems at production facilities (WBG1). A practice that Vitens has deployed to mitigate this is the retaining of hardware from replaced security and PLC systems as a backup inventory, a practice referred to as the cannibalization mechanism. This allows them to address maintenance issues using older components that haven't been discarded, providing a sustainable solution for repairing systems (VIT1).

Manufacturing for abstraction and treatment

In abstraction, the most important manufacturing components are the extraction pumps. These pumps obtain water from the groundwater depth and pump them to the production facility (OAS1). Often these pumps are redundantly implemented, so about 6 pumps are working in a carousel. This is for the durability of both the pumps and the water sources (VIT4). If a well is continuously drained, then it can cause particle blockages in those sources.

The pipes that transport the water to the production facility also fall under abstraction. These require maintenance as much as any other pipelines. To monitor their progress, many models have been developed to predict this deterioration, so that repairs are most cost-effective and substantiated (Philip & Aljassmi, 2020).

An important dependence on this industry also arises when considering the building of a new facility, to meet a higher water demand (PWN1). However, expansion of the production facilities is not a critical process.

Manufacturing distribution

The water sector is not able to easily re-route its supply through another path and is therefore hugely affected by damages and leaks in certain pipes (Baylis et al., 2016). For maintenance and repair of the pipeline and distribution network, the same predictive models mentioned in the review by Philip and Aljassmi (2020) can be used. However, there are instances where maintenance becomes necessary following unforeseen damage caused by unintended accidents. Take for example a recent case at Vitens, where construction work accidentally damaged a pipeline, causing a huge leakage and leaving many households without water (NOS, 2024). There are also cases where decisions on early pipeline maintenance or replacement need to be made, as a result of the repairing of the electricity network, as previously mentioned.

2.4.6 People

An indispensable dependence of the water sector exists in people. Their expertise and specific knowledge are of utmost importance in maintaining the continuity of the services of the water sector (and many other sectors as well) (Baylis et al., 2016). In addition, the consumers present an important dependency.

Specialized workers

Specialized workers are a valuable asset to water companies, regarding their position in the water production facility. The importance is the knowledge of various fields, as operators need to have expert knowledge across multiple fields, such as automation, electrical engineering, mechanical engineering, chemical engineering, etc. (VIT3). Challenges arise when experienced workers approach retirement age, leading to a significant loss of knowledge within the industry (VIT1). Although measures are taken to record this knowledge, it isn't always possible to record everything (OAS1).

Despite advancements in automation and that certain production facilities can run fully autonomously and unattended, the human factor remains indispensable. During the pandemic, it became evident that staff at production facilities play a critical role in the maintenance of operations (WBG1). Acute calamities require the ad hoc and flexible nature of the workforce to effectively respond, which is an asset that cannot be replaced (VIT2).

Damage to infrastructure also requires a large set of specialized workers with knowledge of the entire system to repair it. If those workers are not there, decisions may be made that are not well-informed (VIT3).

Consumers and water demand

From the perspective of a water production facility, the demand of consumers is important, because, without consumers, there is no need to produce water. However, if entire delivery areas are evacuated, there is still a requirement to keep pressure on the pipelines, otherwise, it might affect the quality of the water and the durability of the pipes (WBG1).

Put simply, if demand increases, more water is needed. There is a high amount of uncertainty regarding demand changes (Vonk, Cirkel, & Leunk, 2017; Baggelaar, Kuin, & Geudens, 2022). Tangena (2014) from RIVM modeled the degree to which demand is being met by water companies in 2040 and estimated an increase which was calculated based on the current demand for water and the expected population growth. In a later report by RIVM in 2023, it was found that in some regions in the Netherlands, a growth of 30% was already seen after just 10 years (van Leerdam, Rook, Riemer, & van der Aa, 2023). They attribute this sudden change to an unforeseen increase in dry summers, affecting the water demand greatly (van Leerdam et al., 2023).

Climate is considered a significant factor influencing changes in demand, as Niknam, Zare, Hosseini-nasab, Mostafaeipour, and Herrera (2022) state, there is a clear correlation between weather and water use, which determines water demand. Mishra et al. (2021) determine that changes in urban population will increase water demand, and increase the volume of wastewater in urban water systems. Birkett (2017) also mentions that the demand for water resources is increasing relative to the demographic pressures of population growth. He also mentions the role of an anticipated increase in living standards within individual countries, which also increases drinking water consumption (Birkett, 2017). Zimmerman (2009) relates income to a driver in water consumption, where high-income countries withdraw almost double the amount of water per capita than middle- or low-income communities.

In the research done by Agudelo-Vera, Mesman, Blokker, and Adamse (2017) it was determined that in the case of a nationwide blackout, where no electricity is available for a long time, the water demand is halved. That is because the outage disrupts not only household appliances but also communication and remote-controlled processes, significantly impacting societal activities. During a blackout, economic activity declines sharply as people cannot go to work, production facilities close, and offices, schools, and universities remain shut due to heating and communication limitations. In the event of a complete blackout, daily consumption drops by approximately 50% after a day, and leads to a further 25% drop after 3 days of continuous black-out (Agudelo-Vera et al., 2017).

During periods of high water demand exceeding capacity, an emergency measure may be to temporarily reduce the pressure to ensure at least a continuous water supply from taps, although this is not preferred by water companies (VIT2). In systematic demand increases, it may be required that new production facilities are constructed or a permit for new sources is procured (PWN1).

2.4.7 Financial & banking sector

Drinking water utilities are reliant on finances to upkeep their processes and ensure continuity in delivering water and meeting demands. That is because finances are needed to procure materials, energy, services, and staff, interlinking the rest of the sectors. As a result of one of the collapse narratives (5. Loss of financial stability of water companies), it is relevant to consider the financial & banking sector as an important interconnected sector.

Mechanics increasing the price may appear through the reduction of water supply and/or increase of water demand, however, this is not as simple as this. All households pay for a standing charge and per m^3 usage (OAS1). The price per m^3 is determined by the government, together with the water companies (WBG1). This is because of the need to maintain the affordability of water, as it is a fundamental necessity for people, and it must remain accessible to lower-income populations. Societal collapse effects may have many (in)direct consequences, which can affect the price of water. Too high prices may exclude a group from being able to pay for their water, which might lead to water theft or other consequences.

From a different perspective, the banking and financial industry is very closely related to the Telecommunication & IT infrastructure, as modern banking relies on online money rather than tangible currency (Birkett, 2017). A disruption in that sector, perhaps prompted by a power outage, may affect the banking sector to continuously provide the financial income for water companies to continue their operations.

CapEx

Capital Expenditure (CapEx) involves investments in fixed assets for long-term benefits, like machinery or buildings, affecting future business growth and appearing as assets on the balance sheet (CFI & Schmidt, 2022). For water companies, large investments include building a new extraction well or a new production facility. Thus, capital expenses depend on the state of the infrastructure, the need for infrastructure expansion, and the capacity of the water utility to acquire financing for the investments.

Water companies face significant challenges due to inflation, which has substantially increased the cost of replacing assets acquired in previous years (VIT1). Additionally, the regulated and gradual increase in water costs further limits available funds for future investments. As a result, water companies are encountering difficulties in maintaining financial stability and meeting their investment needs (VIT1). On the other hand, high energy prices of the past year in the Netherlands led to many households being extra cautious with their energy usage in-house. As a side effect, households tended to shower less or shorter, which led to reduced water usage (VIT1). This in turn reduced the available income for water companies. The difference between a dry and hot summer vs. a rainy summer, or a lockdown where many people are working from home or commuting to work in other cities, can strongly impact the revenue of that year (VIT2).

OpEx

Operational Expenses (OpEx) refer to all expenses for day-to-day costs of operation, which can be fixed or variable, but are specifically related to enabling water production and distribution every day (CFI & Schmidt, 2022). In this case, it refers to all short-term expenses a water company may make to keep operations running. For water utilities, the operational expenses are paid from the fees that their customers pay. Therefore, these depend strongly on the customer's willingness and ability to pay, through the banking system.

In emergencies, where instant repair is required to ensure that water demand can still be met, money is immediately made available and falls under OpEx (OAS1). Due to the possibility of infrastructure damage that needs to be repaired and continuing maintenance, the costs of upholding operations may exceed the financial reserves of water companies. As a result, a high dependence on OpEx might endanger the availability of CapEx in the future.

In a non-societal collapse scenario, there are always financial safety nets, through loans and subsidies, especially considering the semi-public nature of water companies in the Netherlands (Drinkwater Platform, 2022). However, this indicates a reliance on the continued workings of the financial and banking sector and the central government behind it.

2.4.8 Transportation infrastructure

Transportation is important for the water sector as it delivers the required chemicals and parts and allows for workers to arrive on-site or at other sites that may require maintenance or other operations (Baylis et al., 2016), but also fuel that is required to keep emergency generators running (VIT4). Disruptions in transportation, such as strikes, can significantly impact these deliveries, potentially leading to delays or shortages (WBG1). Additionally, if delivery schedules are optimized to coincide with storage running out, as a cost-saving measure, it could inadvertently limit operations if supply fails for a long period. Transportation is also required for the construction and maintenance of the network. Despite this dependence, risk analyses performed by water companies do not always account for transportation-related vulnerabilities (VIT1).

One of the uses of transport at water treatment facilities is the disposal of residuals. Sludge, for example, can only be stored at these facilities for a limited time. This residual material is collected and recycled into new material, such as road tarmac (Oesterholt, 2017). Most treatment plants do not have the facilities to process this on-site (URS, 2010). A disruption of transportation will require treatment plants to store the sludge or dispose of it elsewhere which may not be possible (URS, 2010). For the water production facilities for drinking water production, the amount of residuals is limited (VIT2). In most cases, residuals do not form part of the primary process, these may be dumped or disposed of as best as possible (VIT2).

2.5 Main points chapter 2

- Societal collapse is a conceivable event, considering the transgression of planetary bounds along with over-complication and complexification of interdependent infrastructures. It poses a high, existential risk to modern societies.
- What causes societal collapse is outside of the scope, due to the high uncertainty and plethora of reasons that may cause it. Instead, only the scenario elements are considered as possible consequences of societal collapse.
- The water sector, as a basic human necessity, is an integral part of society that should withstand or adequately respond to pressures from a collapsing society, to not further exacerbate the detrimental effects.
- Although drinking water companies already take many measures to ensure resilience after disruptive events, water companies fail to consider the implications of long-term trends, requiring a high adaptive capacity from water production facilities. Many current resilience measures are found in robustness and redundancies.
- The water sector is heavily dependent on: the environment; telecommunications & IT infrastructure, both internal and external; energy, as electricity and fuel; chemicals for treatment of water; manufacturing for pipelines and machinery; people, in offices and at production facilities; financial and banking sector, for long and short term expenses and finally transportation; for movement of goods.
- The performance of the water sector is not affected by gas supply and consumers' demand for water, despite being dependent on these components. This dependency does not lead to any direct loss.
- In cases of acute emergency, the most important sectors are those that are on the operational end, as drinking water companies rely on their ability to maintain the production of water. This translates into a dependence on specialized workers. As the disruptions continue, dependence moves from workers toward energy, chemicals, and manufacturing. In other words, the time scale is of great importance when considering dependencies.

3 | Model Description

This section explains the model that translates the findings from chapter 2. To start, the approach will be explained, which includes explaining the use of Exploratory Modeling and Analysis (EMA). The model consists of two main elements, the water production model, which models the process of water production, and the network model, which influences the water production model. The water production model is developed with System Dynamics modeling, and the network model is a graph model of connected components. These will each be elaborated on.

Chapter 3 strives to answer subquestion 3: *How can the water system and its interdependencies with other sectors be represented effectively?*; and subquestion 4: *How can the dynamics within and across the interdependent sectors be determined and represented?*; by taking a modeling approach that considers an interdependent water sector and specific dynamics within and across these sectors.

3.1 Modeling approach

The chosen modeling approach is exploratory modeling, where the goal of the model is to explore if certain realities occur in certain ways. Given the high uncertainty related to societal collapse and the high level of complexity with many assumptions and many unknowns, any model that emerges is likely not suitable for making predictions or concretely analyzing the effect of policies. The goal is therefore to explore this modeling technique which can provide insights into how such a complex system could be modeled.

The Exploratory Modeling and Analysis (EMA) approach comes with a developed workbench that aids the modeler in testing their model. It is based on a research method that uses surrogate models of the real world to try to mimic the behavior of the system for analysis (Agusdinata, 2008). The problems being modeled (specifically from a policy standpoint) are in their nature ambiguous and uncertain, for which EMA provides tools to analyze this and make computations of plausible outcomes and system representations (Agusdinata, 2008).

EMA utilizes the following framework, which should be established to research the system. The framework can be seen in figure 3.1.

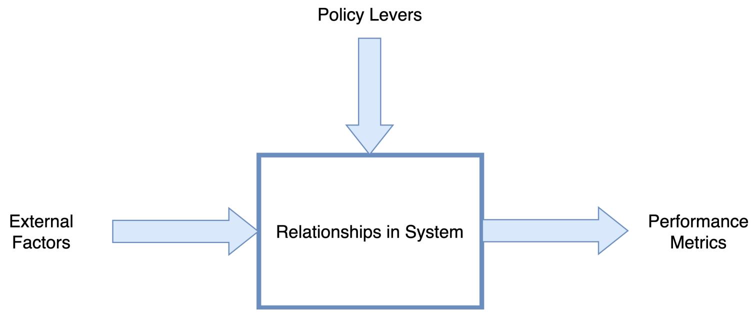


Figure 3.1: Exploratory modeling framework adapted from Kwakkel (2017)

External factors can be seen as uncertainties. A scenario is then created which is essentially a point in the uncertainty space. The levers are examples of policy measures that can be implemented to mitigate certain negative effects. The levers are of the same type of parameters as the uncertainties and a single policy is a point in the lever space. The policy levers are outside of the scope and could be implemented in future research.

It is important to note that a single model run, where a scenario is developed, is not necessarily a “prediction” of the future, but rather an experiment of what would happen if certain uncertainties obtain certain values (Bankes, 1993).

3.1.1 Conceptualization

The conceptualization refers to the general approach to modeling the sectors and their interactions. It also includes the scoping of the system. It provides a top-level view of what is being modeled.

Explicitly, the purpose of the model is to answer the research question, which relates to understanding in what ways the water sector responds to pressures from societal collapse, through its interdependent sectors. Although many models exist that attempt to analyze the behavior of individual infrastructures, more models are needed that allow the coupling of multiple interdependent infrastructures (Zio & Sansavini, 2011).

Zio and Sansavini (2011) identify 6 main streams of modeling interdependent infrastructures, of which this approach falls under the second stream: dynamic simulations, which examine infrastructure operations, the effects of disruptions, and the associated downstream consequences. The focus is on capturing the dynamics of cascading failures through disruptions propagating through the interconnected system.

To start, the only sectors that were considered explicitly in the model are depicted in figure 3.2, with their respective components.

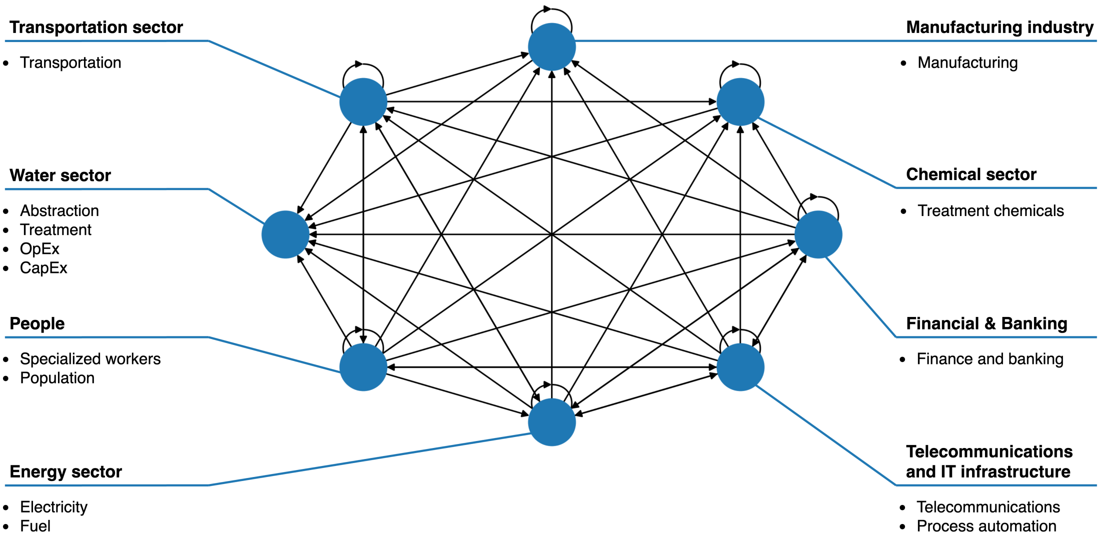


Figure 3.2: Components within each sector

Each node in the graph represents a sector module, which consists of components. These modules interact through links. A link is bi-directional and points from one sector to another if there exists a component within that sector that is dependent on a component from another sector. Each sector module can exchange information between its neighbors, and influence its neighbors. The modules do not represent these sectors on any notion of physical space. The importance of the model is how the states of the different sectors can affect the states of other sectors.

The model should allow for cascading failures. A conceptual model in figure 3.3 shows how disruptions can propagate to third-order systems. The initiating event is in this case disruptions from societal collapse. The difference is that these disruptions happen over a longer period of time, as well as the cascading failures.

For this research, the modules are fictitious, hypothetical instances that contain the elements of each sector, but are not specifically spatially bounded or connected to real-life objects. The actual real-world equivalent of what is being modeled is not relevant and may be a matter for future research. The finalized model could be a starting point for a more detailed multi-model ecology, where each module can be replaced with a more specific model that can more accurately represent that sector, and links allow for information flows between these sectors. The only information that flows between sectors is the state of each component. The relationships in the model would be the response to the state of a linked sector. The response to a state is deterministic.

In addition to this, the physical space where these sectors are located and the movement of physical

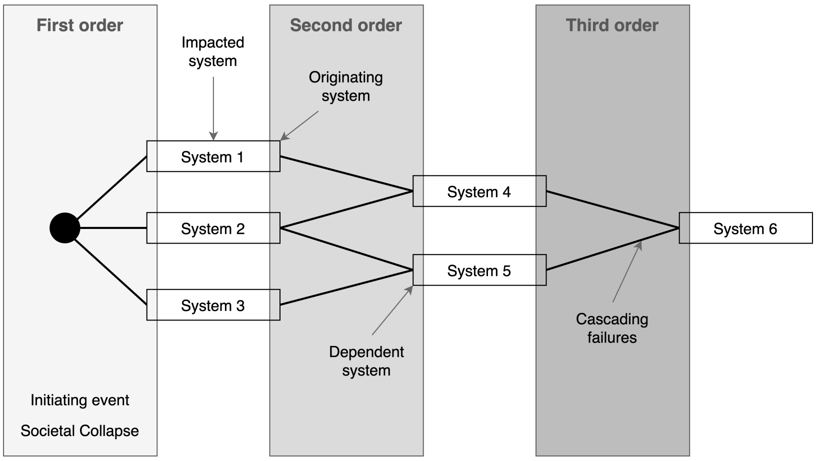


Figure 3.3: Conceptual model of cascading failures, adapted from Johansson (2022)

objects between them is not relevant. What is key in the model is that there is a response to disruption, which could be interpreted as a decline in deliveries, but not necessarily modeled as that.

The model serves to simulate how changes in performance from components, as a result of disruptions, can propagate through the connected network. A disrupted component upon which another component is highly dependent has a large influence on the performance of the latter component.

3.1.2 System boundaries

When studying complex systems, defining the boundaries is a crucial step in the conceptualization, as it defines the scope and limits of the model under consideration. It increases the understanding of what exactly is being modeled and how such a model may represent reality. An effective system boundary must be defined to ensure that all important elements are incorporated, whilst still being relevant. As models are always a simplified version of the real world, it is integral that what is modeled is enough to be able to draw certain conclusions without straying too far from reality. Four aspects of the system boundaries are discussed below.

External boundaries

The model is scoped to focus on the drinking water sector and its interdependencies. Dependencies of the other sectors that are not related to the water sector are not relevant. Furthermore, the cause of a societal collapse, and what mechanisms lead to a collapse in the first place are outside of the system. The external boundaries are limited to the disruptions to components, as well as population dynamics and water availability.

Internal boundaries

The interdependencies of the sectors between one another affect the performance of other sectors. Some disruptions are kept outside of the model. For instance, only the chemicals required for the water sector to treat its water are modeled. These are considered water sector-specific components. On the other hand, there are model-wide components, where that component's supply is modeled to be to all other components. The division is shown in the table below.

Model-wide components	Water sector-specific components
Specialized workers	Automated processes
Electricity	OPEX
Fuel	CAPEX
Telecom	Chemical
Financial and banking	Manufacturing
Transportation	Abstraction rate
	Treatment rate

Table 3.1: Component scoping

If, for example, the energy sector cannot provide electricity to the water sector following mechanisms that unfold in a societal collapse scenario, then it is acceptable to assume that other sectors also do not have electricity. If there is an issue with the delivery of a specific chemical required for treatment, it cannot be assumed that all chemicals required by any other component are also disrupted.

Spatial boundaries
While the model is not restricted to a specific geographical location, it is based on the interdependencies of the water sector in the Netherlands. That is because all of the information gathered for chapter 2 is based on the Dutch water sector. The physical representation of the modeled infrastructures is not important for the study. The model represents a fictitious water production facility with input from the sectors it depends on. Where this facility is located is outside of the system boundary.

In addition, there is no notion of space in the model. The distribution network of the drinking water sector is therefore outside of the scope, as well as road networks, power lines, etc., and their lengths and/or distances. Furthermore, climate factors could be included in the model that are relevant to water availability in the future. Despite this, it is not explicitly modeled as that would require a physical location upon which to base the climate information.

Temporal boundaries
The model is designed to simulate the progression and effects of a societal collapse over an undefined period. This ambiguity is intentional, as it reflects the uncertain nature of the collapse's time frame and progression. Since the cause of the collapse is outside the scope, the time frame of a collapse is also outside of the scope. Instead, time steps represent state changes. The total simulation time is therefore not fixed, determined by the sequence and impact of state changes rather than actual time.

3.1.3 Model requirements

The model requirements help to translate the model concept into an actual model, and detail what is needed to be able to model such interactions. This is also useful if the model is to be replicated in the future.

To summarize, the model should:

- Allow for insight into how disruptions can cascade through the network due to dependencies.
- Model how societal collapse scenarios cause disruptions.
- Incorporate dynamics between sectors that allow for complexity.
- Model enough sectors with enough variability in their dependencies to result in emergent behavior.
- Model the production process of water, and how water flows from source to tap.
- Account for resilience, redundancy, and adaptation measures from the water sector.

In short, a model is required that can, at a very high abstraction level, give insight into how dynamics between sectors, components, and their dependencies are shaped. The model should be able to translate how disruptions, caused by societal collapse, can cause problems down the line of dependencies, affecting the water sector's ability to meet the demand. There is no need to accurately incorporate a notion of space, where objects travel to other locations. What is important is that the model can respond to multiple scenarios of different levels of disruption to components, to analyze how these effects reverberate through the model.

In principle, the sectors themselves can remain relatively simple, where disruptions are modeled as exogenous effects resulting from the scenario space. However, it is also possible that these become endogenous effects by applying a more intricate model that more effectively translates disruptions from dependencies to disruptions in their services. To achieve this, the model needs to be modular enough that nodes can be exchanged for more detailed submodels.

As a result, the model outcomes of interest are specifically related to the water sector, as they are never directly disrupted, but always through other disrupted components. The outcomes of interest are thus; the performance of the water sector's components, which are abstraction rate and treatment rate, each with different dependencies.

3.2 Water production model

The water production model is a submodel that contains more detail than the other nodes, to demonstrate the capacity of the network model to communicate with submodels. The water production model simulates the four steps to water production, which are; water abstraction, treatment, storage, and distribution. It represents a hypothetical water treatment facility, that makes use of traditional water treatment from groundwater. The actual distribution network of the submodel is outside of the scope, as there is no notion of physical space. Therefore the distribution step is modelled as a sink where the flows stop.

The submodel contains specific requirements that need to be satisfied to effectively capture the dynamics within this specific node. It is required to contain information on how water flows from the source and is treated before entering distribution. It needs to be sufficiently limited in its production due to three constraints:

1. The abstraction rate or treatment rate is not sufficient to produce enough water.
2. The amount of clean, uncontaminated water is not sufficient to produce enough water.
3. The demand is too high to produce enough water.

These dynamics should drive water production. The submodel also allows for the integration of more complex climate dynamics, where precipitation and evapotranspiration affect the groundwater supply, so climate effects can be incorporated as an additional constraint.

3.2.1 Implementation

The submodel is created using System Dynamics (SD) modeling. SD is a method that can describe, model, simulate, and dynamically analyze complex systems with stocks and flows (Pruyt, 2013). SD modeling is often used to learn about a system and the link between system structure and behavior (Pruyt, 2013). Although more detailed models exist that can accurately model the movement of water from groundwater to distribution, the high level of detail required for these models was not relevant for modeling this step. SD can help to create a more simplified version of the process while incorporating the key requirements that were listed above.

SD is especially useful in incorporating feedback loops, and dynamic variables. In the critical review by Phan, Bertone, and Stewart (2021), 169 SD models related to water were reviewed and categorized on what they modeled. Several models consider the hydrologic system in combination with population and demand dynamics. They specifically considered; the environmental influence on a water basin, where precipitation and evapotranspiration determine the water balance (Keyhanpour, Musavi Jahromi, & Ebrahimi, 2021; Kotir, Smith, Brown, Marshall, & Johnstone, 2016; Xu, Seibert, & Halldin, 1996), and water level variations due to demand (Alifujiang, Abuduwaili, Ma, Samat, & Groll, 2017; Sehlke & Jacobson, 2005). Many studies look at the effect of certain policy levers on the use of water and their influence on water levels, but these were not relevant to this model. These studies consider a finite water resource and model the addition and subtraction of water, however, there do not exist many models that attempt to model this as simply as is required for this submodel. The aforementioned sources were examples used in the creation of this submodel.

SD provides a useful platform with which to constrain flows of water as a result of performance dropping or water sources being contaminated, without requiring an understanding or integration of a much more complex model. For this implementation, what is important is that the three constraints listed above determine the flow at the steps abstraction, and treatment, to finally determine which reaches distribution.

System Dynamics model

As explained before, the system dynamics model models the process of groundwater abstraction, treatment, storage, and distribution. Figure 3.4 demonstrates the implementation of the SD model using Vensim, an SD-modeling software (Ventana Systems).

The model is influenced by several external variables, displayed as model input; abstraction rate, treatment rate, and demand.

To start, water is abstracted from groundwater. In the Netherlands, about 80% of water is abstracted from the groundwater (Noordhoff, 2021). Within the SD model, there is a small environmental submodel, that encapsulates very simply the effect of precipitation and evapotranspiration of the water level in groundwater. This submodel serves as a placeholder for more detailed models that exist which can

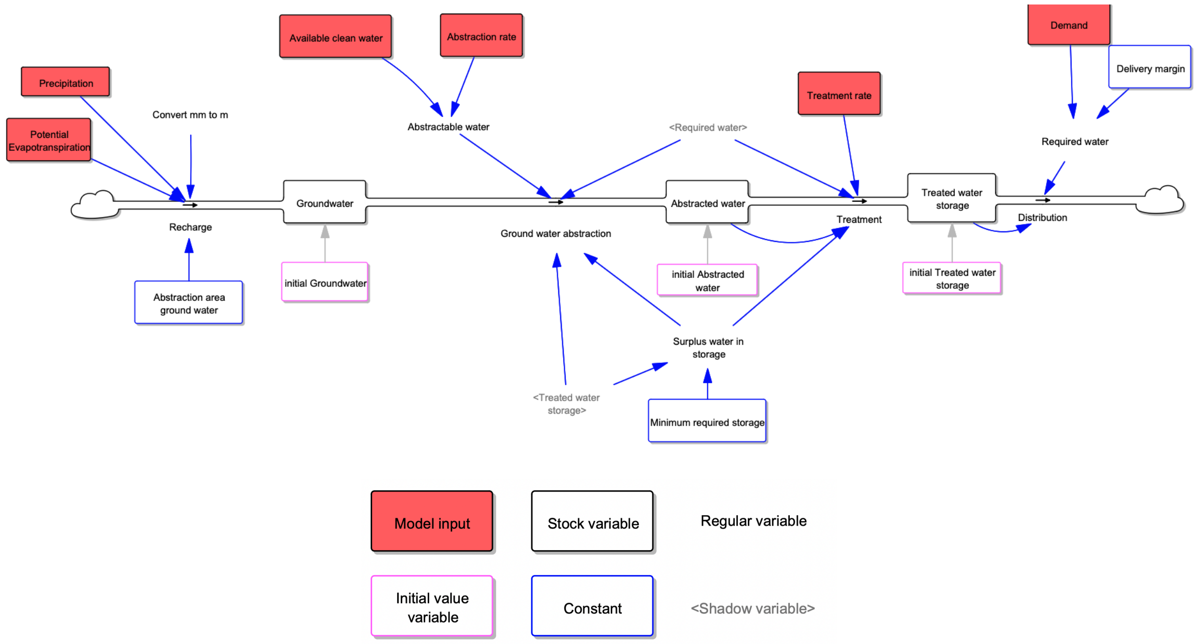


Figure 3.4: Water production model in SD

effectively understand specifically how climate can affect the groundwater level, and the amount of water available. The groundwater source is chosen to be modeled as infinite, so even though climate effects are included, they do not change the groundwater level. These models exist, and could effectively be coupled to accurately model the groundwater source (Stofberg, Pronk, van Huijgevoort, Raat, & Bartholomeus, 2023), however, these are too detailed for the current modeling approach and could be implemented in future research.

To constrain the available water, the clean water available variable represents the fixed amount of water that can be abstracted. The base value of clean water available is determined by the multiplication of base population with base demand, multiplied by 10. This means that at any point if there is no contamination, there is enough water available to meet 10 times the base demand from the base population.

The abstraction rate determines how much water can be abstracted from the groundwater stock, as well as the available clean water, which represents a finite source of groundwater available, that is not contaminated. As water is abstracted, it is prepared for treatment. The amount of water that can be treated is also limited by the treatment rate. Finally, water enters storage, where a minimum storage amount is required. The water that exists in storage is determined by distribution, given by demand with a delivery margin of 10%.

3.2.2 Water model assumptions

One of the key assumptions in the water model is that **the source of groundwater is infinite**. In reality, this is not the case. There are many more complex processes occurring in the water cycle that are simply not applicable to model using SD. One can assume that the existing groundwater reserves are so abundant that abstracting water for use has a negligible impact on the total supply.

In the environmental model, **the potential evapotranspiration is assumed to be the total evapotranspiration**. In reality, evapotranspiration is dependent on a multitude of things, such as soil conditions, cloudiness, radiation, etc. This level of detail is not relevant to model this exactly, as it serves more as a placeholder for a more intricate model. As stated previously, there exist more intricate models that can exactly calculate the groundwater level and the amount of water that flows daily, but this is too complex for this model.

A key driver in the model is the **minimum required storage**, which is assumed to be half of the base daily demand for the base population. This is because it can ensure that there is always at least enough water at any time during the day to provide half of what is daily required for the base population. It can allow for enough buffer during peak demand hours.

Another assumption is that there exists **a delivery margin of 10%**, when in fact, the amount of water delivered is determined by the minimum pressure that needs to be maintained in the pipelines. However, as for the previously mentioned assumptions, these requirements are satisfied by implementing a much more detailed model for water production.

3.3 Network model

In the realm of models that attempt to encapsulate interdependencies between critical infrastructures, there is a subcategory regarding networked-based approaches. These approaches try to infer information of dependencies where nodes represent differing elements (components, sectors, assets) and links represent relations between elements (Setola & Theocharidou, 2016). The biggest advantage of this modeling approach is the relative simplicity and inductivity of relative assumptions (Setola & Theocharidou, 2016).

The network model made for this research comprises of interconnected sectors with certain dependencies. The sectors are composed of components, as was seen in figure 3.2.

Dependence, as defined by Rinaldi et al. (2001) can be physical, cyber, geographic, and logical. In the case of such components within sectors, dependence can be interpreted as the need for material input of that component, the meeting of demand for that component, or reliance on that component to be able to carry out functionality.

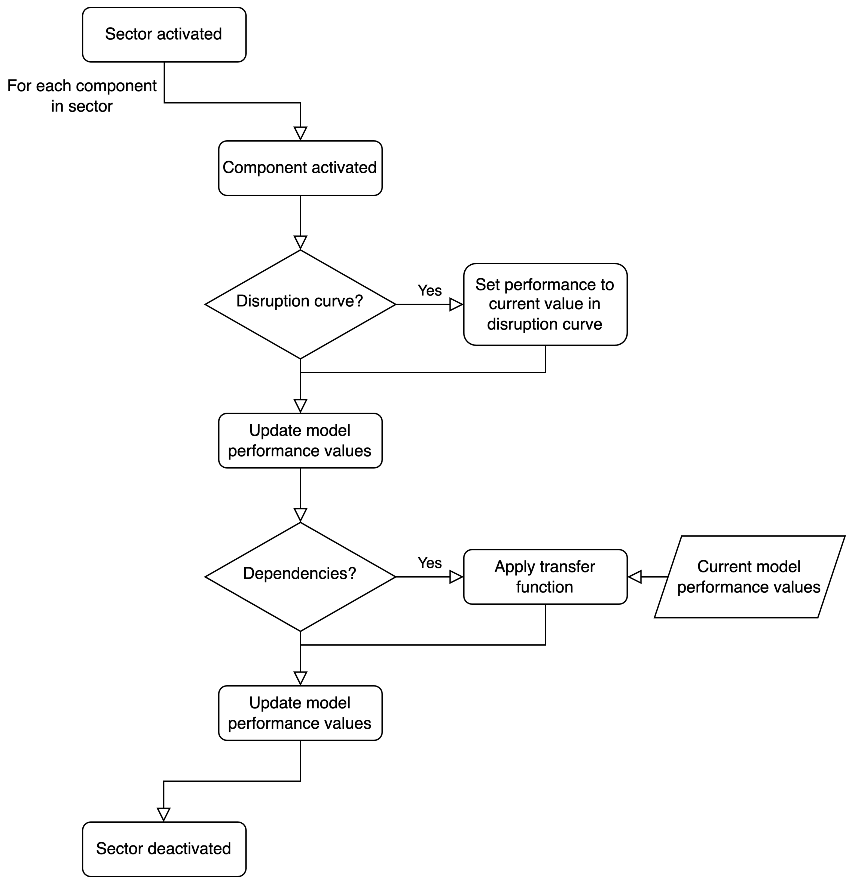


Figure 3.5: Model activation flow chart

Each component is contained within a sector module. The activation of a node follows the flow chart in figure 3.5. To mitigate the effect of a bias by predetermined activation, the activation of sectors occurs randomly. Each sector then considers the change in performance of its components, also activated randomly. However, as the water sector model is dependent on all components and nothing is dependent on it, it is activated at the very end. This is done because the model is made based on the perception of the water sector toward its dependencies, solely for the production of water. It does not consider the outward dependencies that other sectors may have on water, as it is not relevant to the production of water.

In a single time step, each sector is activated in a random order, and so the performance values are updated at each step until finally, each component has had a turn. A time step could represent real-life time, but it is not a requirement, as the relationships are arbitrary of time. It can help to understand the speed of decline as disruption is modeled relative to time. For example, if a slower decline is desired, time steps can represent months. It is crucial to note that both climate effects and population decline, when modeled, are time-dependent and should be adjusted to reflect realistic values for the desired time step length, ensuring their proportions align accurately with the considered period.

3.3.1 Dependency matrix

Several modeling approaches make use of a matrix of dependency scores (Setola & De Porcellinis, 2008). Guidotti et al. (2016) utilizes a component functionality weight that represents the contribution of restoring component i to the functionality of component j. This weight depends on multiple factors and can be determined in multiple ways. However, for complex networks, this assumption of static functionality weight may not be valid, and it may be more logical to make this dynamic (Guidotti et al., 2016). Despite this, it allows for relative importance to dependencies.

In this model, the network dependencies are determined by the dependency matrix. This square matrix i-by-j comprises of columns and rows equal to the number of components. Each cell represents a weight factor w_{ij}, which signifies the dependency weight of how dependent component i is of component j. These weights represent what level of dependence exists, where a score of 10/10 would be the maximum and 1/10 minimum. A weight of 0 represents no dependency relationship exists. The dependency matrix determines the dependencies of the model and is part of the input. This means that the value of w_{ij} for each i and each j is defined by the modeler. The matrix topology, which refers to all the cells that have a $w_{ij} \neq 0$, indicates the dependencies between components. For a dependency to exist, there must be a weight greater than 0. The weight factor is an integer value. These are interchangeably referred to as the dependency coefficients.

3.3.2 Performance levels

In the literature, representing functionality can be done in multiple ways, where Schotten et al. (2024) identify three main approaches: binary functionality states, discrete functionality states, or continuous functionality. These functionality states measure the degree of failure caused by disruption, quantifying this abstract concept (Schotten et al., 2024).

In several modeling approaches, researchers utilize the continuous functionality concept of inoperability. This is a generic term referring to the expected decrease in functionality if a component j, on which component i depends, experiences disruptions (D'Agostino, Cannata, & Rosato, 2010). The advantage of defining inoperability is that it allows for a single abstract parameter to represent diverse ways in which a sector may be affected (Setola & Theocharidou, 2016). A modeler can represent various types of dependencies but only considers a single effect of that dependence, which is the inability to operate at maximum performance. The lower the inoperability value, the better the i^{th} infrastructure can maintain some operational functions (for example, through the use of buffers, backup power, etc.), even when the sector j it depends on is inoperative (Haimes et al., 2005; Setola & Theocharidou, 2016). The use of inoperability metrics may provide non-trivial insights on the basic mechanisms driving system response to disruptions, where more complex and accurate abstraction models may hide the origin of the phenomena (D'Agostino et al., 2010).

Nan et al. (2014) utilizes a "measurement of performance" (MOP) which is the inverse of disruption. They explain that examples of this MOP can be the availability of critical facilities, the number of customers served, the connectivity of the network, the level of economic activities, etc. (Nan et al., 2014).

In this modeling approach, performance is considered as the inverse of disruptions. This allows the modeler to simulate cascading failures, through the propagation of such disruptions, or a reduced performance. Using a continuous variable further enables the dynamic simulation of the component's functionality over time, which is a model requirement. As a result, the model can capture nuanced changes and trends in infrastructure performance, without needing to define exactly what the performance relates to.

Thus, in the model, each component has a performance level. It is measured on a continuous scale from 0 to 100%, where the closer a performance level is to 100%, the better the component functions, as it is non-disrupted. In cases where the demand for the component is greater than usual, a component can meet this demand depending on the performance level; the better the performance, the more capable the component is of satisfying the higher demand.

The performance of a component is impacted by the disruption it experiences or the disruption of the components on which it depends. Both cause a reduction in performance and both are seen as disruptions. As a result, a component can only perform at 100% if it is not disrupted, and if the components on which it depends are not disrupted. Performance can increase if a component becomes less disrupted over time. This decrease in disruption over time relates to the ability of a component to recover and restore functionality after a societal collapse. Exactly how a component can do this is irrelevant, hence the flexibility in the interpretation of the performance values.

The interpretation of the performance levels can be flexible, which accommodates various ways to measure the performance of a component. It means that the model does not need to be explicit about what is causing changes in performance levels. It does not require any understanding of how a component is used for the production, distribution, or any process that contributes to the performance level of another component. This allows for the sectors to be coupled in an abstract way that can still facilitate complex behavior, as disruptions propagate through the interdependent system.

3.3.3 Network model assumptions

To apply such a networked modeling approach, there must be assumptions made regarding **the topological model of an infrastructure**, i.e. what are the nodes, what do they represent and how are they connected, and **the coupling mechanism** existing among the nodes of the network, i.e. how the first node is linked to the other node and how it communicates information (Setola & Theocharidou, 2016). These assumptions are also present in the network model, as the determining of the dependency matrix topologies and the values of the w_{ij} is partially based on assumptions.

Another key assumption of the network model is that cascading failures can only occur if there is **an established pathway of links** connecting the component of interest to a disrupted component. If there are enough disrupted components, then these cascading failures can accumulate to cause emergent behavior, which is a requirement of the network model.

The network model also assumes **no dependence on the water sector's performance**. This is due to the perspective of the water sector as the production of drinking water only for consumers. The model is scoped to represent the production of drinking water for consumers. Therefore the performance of the water sector does not affect the performance of any other component directly.

3.4 Transfer functions

Components are affected by the performance changes of the components upon which they depend, as they need input from these components to function. The impact of the disruptions on a component is determined by its response to reduced input. This impact can be quantified through a detailed submodel that simulates the reduced input's effect on the output. This requires a rich understanding of available models for sectors and would require the coupling of different model types and techniques. For simplicity, this can also be approximated through a transfer function that aims to capture the influence of a reduced input on the output.

To approximate the effect, a deterministic relationship is assumed. This is because, given the high level of uncertainty within these relationships, and the ambiguity on how such elements are connected, a probabilistic inference requires the assumption of too many parts, and may lead to a loss in interpretability of the conclusions. The decision to use a deterministic relationship is to prioritize clarity and directness.

Quantifying this uncertainty and determining how disruptions propagate through a system is crucial in understanding and representing a system's response to disruptions (Zio & Sansavini, 2011). To approximate how components respond to a reduced input, several approaches to the transfer function were established. Given that each strategy to translate performance losses from disrupted components to interdependent components is based on different philosophies and assumptions, one strategy can be advantageous over another, but none can be said to exactly represent reality.

These functions serve to translate the performance levels of all components that component i is dependent on, so it is used to calculate P_i, the performance of component i. The functions consider the set X consisting of all the components that i is dependent on. These components $j \in X$ each have a performance value P_j. The transfer function calculates a new P_i, based on the set of X and the associated w_{ij}. This is done for each component in each time step.

As shown in figure 3.5, the performance of a component is first affected by disruptions, if it is part of the set of disrupted components. The performance of P_i is assigned to the current performance value for that time step. Afterward, the effect of the dependent components in set X is calculated. To consider the effect of its disruption, it is itself considered within the set X as a component that affects its performance. Thus, the new performance value of component i is calculated by, not only the components it is dependent on, but also the disruption it is itself experiencing.

To approximate the effect of a reduced input to the output, three different approaches were selected. This is done to explore a variety of theoretical perspectives and assumptions. Using a diverse set of transfer functions will enable the evaluation of how complex these transfer functions need to be to incorporate dynamics between sectors that allow for complexity, which is one of the model requirements. These variations and their respective assumptions are outlined in the next sections.

3.4.1 Multi-Factor Linear

In the multi-factor linear, as the name suggests, all factors are considered linearly. The performance of component i, P_i, is equal to the weighted average of all the components in X, the set of components that i is dependent on. It considers the notion that if a single component can increase its performance, then component i might be able to restore its performance, despite other components performing badly, and vice versa. To illustrate, the water sector may be dependent on multiple components to upkeep its performance. If, for example, the automated processes at the production facility are disrupted, the water sector is affected, but only by a fraction, as long as the other components are still performing well.

The weights determine how much the performance of component i changes. The weight, divided by the maximum assigned weight in the dependency matrix - in the example, 10 - signifies how much the performance changes. This fraction is multiplied by the difference between the performance of component i and the performance of the selected worst-performing component j. The weighted average is taken of all the values, which results in the new performance value.

The resulting function is thus:

$$P_i = P_i - \frac{1}{|X|} \sum_{j \in X} ((P_i - P_j) * \frac{w_{ij}}{\max(W)}),$$

where P_i is the performance of component i, P_j the performance of component j, and w_{ij} the associated weight or dependency coefficient of component i dependent on j. X is the set of components on which component i is dependent, and $|X|$ is the cardinality of the set, which equals the number of components contained in the set. And finally, W is the set of all the dependency coefficients in the dependency matrix.

3.4.2 Multi-Factor Non-Linear

In the linear approach, the weights, w_{ij}, of each component in the set X are applied linearly, assuming a direct proportionality in their influence on performance. In contrast, applying a non-linear function to these weights allows for modeling the impact of components in X in a way that reflects more complex, non-linear responses to changes in input. This non-linear approach aims to test a different approach that could capture the non-linear dynamics of how reduced inputs affect component performance, and perhaps add more complexity to the model. The underlying assumption is the same as for the Multi-Factor Linear approach, yet the contribution of each performance value of the set X is different.

The function that the weights are applied to can, for example, scale higher weights to have more importance. One such implementation is the use of an S-curve, also known as the Sigmoid function, which transforms the values of the weights such that more importance is given to higher weights and less importance to lower weights.

The difference between a linear and Sigmoid approach can be seen in figure 3.6.

The S-curve is an example implementation, however, any non-linear function that transforms the values of the weights could be replaced here. The key is that it translates a value between 0 to 1, to a new value between 0 to 1.

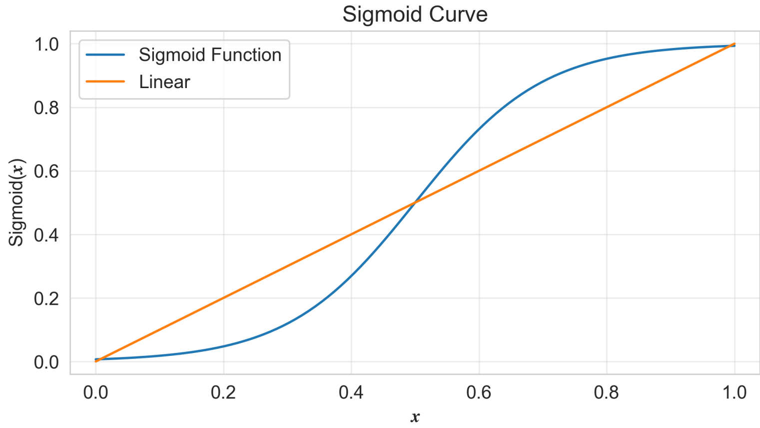


Figure 3.6: Effect of implementing Sigmoid function to x

The formula for this approach is:

$$P_i = P_i - \frac{1}{|X|} \sum_{j \in X} ((P_i - P_j) * g(\frac{w_{ij}}{\max(W)})),$$

where $g(x)$ is, in the Sigmoid case:

$$g(x) = \frac{1}{1 + e^{5-10x}},$$

where x is equal to $\frac{w_{ij}}{\max(W)}$.

In a similar fashion to the non-linear approach, the weights have a relative and a direct approach.

3.4.3 Single-Factor

The single-factor approach considers only one performance value from the set X, hence, a single factor. The underlying assumption is that a single component performing badly limits the capabilities of the sector in question. It can be interpreted as that component being the bottleneck. The strategy to determine the worst-performing component j is determined by the P_j and the w_{ij} associated with it. The component's performance is amplified by how dependent component i is on it.

To determine this value, the performance values for all components are divided by their associated weight. This produces a score from which a minimum can be chosen. This minimum may be different than simply choosing the worst-performing sector. It is done to try and interpret which component might be the bottleneck, as a component with a low performance coupled with a low weight wouldn't effect the component i as much as another component with a higher weight. As such, the weights assigned to the components in the set X have a relative effect on the choice of which component j is performing the worst.

The transfer function is thus defined as the following:

$$P_i = P_i - ((P_i - P_j) * \frac{w_{ij}}{\max(W)}) \quad \text{for all } j \in X \text{ such that } \frac{P_j}{w_{ij}} \text{ is minimized.}$$

Once the worst performing sector is selected, which is the minimum of $\frac{P_j}{w_{ij}}$, then the weight of component i is altered by a change in performance relative to the weight.

3.5 Main points chapter 3

- The Exploratory Modelling and Analysis (EMA) approach entails that the model is used for exploratory analysis of a system with relationships, on which several scenarios with different values for external factors can be analyzed.
- The requirement for the proposed model is to have a series of connected surrogate models that do not necessarily represent physical entities in a physical space.

- The most important requirement is that the model allows for pathways of interdependence to represent the effect of cascading failures.
- The model uses System Dynamics (SD) to represent the four steps of water production: water abstraction, treatment, storage, and distribution.
- The production of water is constrained by the abstraction rate and treatment rate, demand, and the amount of clean, uncontaminated water available.
- The rest of the interdependent sectors are modeled in a network model. Each sector represents a node, comprised of components, and a link between sectors means there exists a dependence between a component within each sector.
- The topology of this network is defined by the dependency matrix, which consists of weights assigned to each dependency.
- Each component has a performance level that it communicates to all of its connected nodes. This performance level is measured on a continuous scale. This is done to allow for flexibility in the interpretation of what performance is.
- The effect of the dependencies of a given component is determined by the transfer function, which is modeled in three ways.
  - The multi-factor linear approach assumes that all dependent components affect the performance of the given component. The weighted average is computed on a linear scale.
  - The multi-factor non-linear approach assumes the same, but the weights are scaled on a non-linear scale.
  - The single-factor approach assumes that a component is only able to function as well as a bottleneck component it is dependent on.

4 | Model Input

This chapter builds on the model description by explaining the inputs inserted into the model and provides insight into the preliminary sensitivity analysis of parameters. These analyses are conducted to determine if the effect is of such magnitude that the values need to be determined beforehand.

First off, the scenario parameters stemming from the scenario elements from section 2.2.3 are explained, showing how each is implemented to create societal collapse scenarios. Next, the dependency matrix is explained, detailing the proposed topology and various ways to quantify the values. Finally, the possibility of adaptation to the water sector is explained.

Chapter 4 strives to answer subquestion 5: *How can the effects of societal collapse be modeled?* by explaining the implementation of each scenario element. Furthermore, this chapter delves into the model parameters for the experiments, whose results will be discussed in the next chapter.

4.1 Scenario implementation

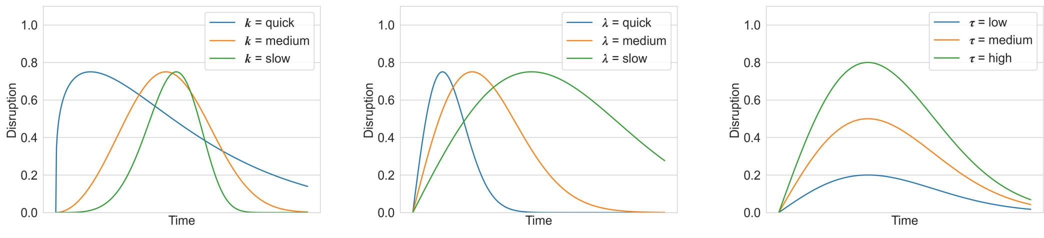
Now that the main mechanisms of the model have been established, the next element to consider is what causes failures, and how are these modeled.

4.1.1 Disruption curves

Societal collapse, as defined in section 2.2, is characterized as a rapid increase in disruption, and a slow recovery, as complexity increases and society rebuilds. Thus, the shape of the disruptions can be modeled as rapidly increasing and slow recovery back to no disruptions.

To simulate such a curve over time, the Weibull distribution function can serve to quantify this type of relationship. Three factors allow the curve to be transformed, which are λ, the scaling factor, k, the shape factor, and τ, the height of the curve. In this context, a higher λ means that the effect of societal collapse is longer and requires more time to recover. A higher k, on the other hand, means a slower rise to a peak of disruption. The lower the k, the quicker "maximum disruption" is achieved. The higher the τ the more disruptions are experienced at the peak.

This is illustrated in the following figures:



(a) Effect k **(b)** Effect λ **(c)** Effect τ

Figure 4.1: Weibull curve transformations

The curves are applied to multiple components. For each component, the shape of the curve is unique. What is key is to define the ranges in which k, λ, and τ can be sampled, as these can be different for each disrupted component, as disruption rates, recovery rates, and size of disruption may differ.

The Weibull curves assume that disruptions subside and that components can recover their performance. This assumption is fundamental to modeling disruptions for each component. This integrated recovery stems from the fact that submodels (apart from the water model) do not have the capability to enhance their performance independently. They are constrained to a performance rate determined by the components on which they depend. No mechanisms within the submodels enable recovery. Thus, recovery is assumed, with disruptions subsiding as components adapt and find new ways to boost performance. The k and λ value ranges may allow for scenarios with long-term disruptions and little recovery. In these scenarios, other components are unable to adapt to the disruptions, and their performance is not able to recover.

When disruptions subside and components are able to increase their own performance, it does not necessarily entail that their previous production capabilities are restored. They do not exactly revert to the complex operations that existed beforehand. It rather means that the sector has found new ways to restore functionality. In the context of this model, the exact ways a sector may do this is not relevant. This is facilitated by the interpretative flexibility of the performance measure.

Modeling complete state changes, where a component is disrupted and fails to recover, necessitates models that are capable of adaptation. Another component might respond to state changes by permanently or temporarily modifying its dependencies. To represent such state changes, disruption curves with an S-curve shape are possible, where components can dynamically change their dependencies to boost recovery. Implementing this approach requires a deeper understanding of the various sectors and their potential for adaptation. To investigate how the current model responds to disruptions and to explore the potential for recovery, Weibull curves have been chosen. These curves make it possible to study the impacts of different disruption paths within the network model.

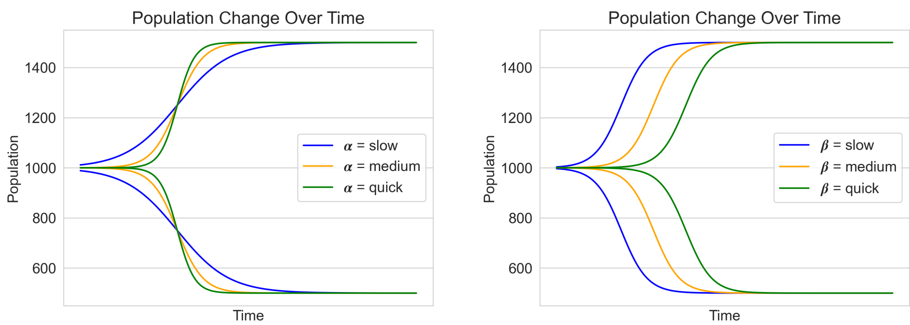
4.1.2 Scenario parameters

The starting point for what causes disruptions is the effects of societal collapse. As the actual cause of the societal collapse is outside the scope, the only thing that is known is what such a societal collapse may result in. These scenario parameters are outlined in section 2.2.3, as list elements 1:8. Together, the parameters form a scenario space under which the model will be tested.

Parameter 1: Sharp increase or decrease in water demand from displaced people

To implement this parameter, there needs to be some effect of population in the model. The most direct influence hereof is to demand, such as the scenario element states. Sharp indicates a rapid change. In a societal collapse, this is a cause of reduced availability of food, water, shelter, and safety, which are related to environmental and social factors. It is likely that the population change occurs early on in the model.

Figure 4.2 demonstrates the S-curve that was chosen to model population change. These curves can be transformed based on α and β values that change the shape of the curve. The ranges of these transformations form part of the scenario space.



(a) Effect α **(b)** Effect β

Figure 4.2: Population change curve transformations

Population is also dependent on other factors: electricity, telecommunications, financial & banking, and transportation. It is assumed that people's livelihoods will be affected if any of these model-wide variables decrease. Frequent blackouts, inability to communicate with friends, unreliable finances, and lack of transportation options, can cause the departure of the population.

Incorporating these effects is done by including the population as a dependent component with a "performance" level. Then the same transfer functions can be applied. Population is not, however, a performing component, and therefore its performance does not affect the rest of the components. In other words, none of the components are dependent on population directly. The dependence on people as workers is the dependence on specialized workers, which is affected by the population as well.

When population levels change, using a single-factor approach may not be suitable since no single factor can be identified as the bottleneck on population changes. Therefore, the methodology is fixed with the multi-factor non-linear approach described in section 3.4.2, where greater emphasis is placed on factors with higher weights for determining population changes.

To translate this into the absolute population change, the percentage change in the performance of the population is used.

$$\Delta P_{pop} = P_{pop}^{t-1} - P_{pop}^{t}$$

The calculated percentage is applied to a maximum of 10% of the current population (based on the curve). Thus, the ΔP_{pop} is then divided by 10 once again. The population change per time step is demonstrated in the following calculation, Given that ΔP_{pop} is maximum 1 and minimum -1.

$$\text{Population} = \text{Population} * (1 + \frac{\Delta P_{pop}}{10})$$

The population is then used to calculate water demand. Water demand is aggregated and simplified to be calculated as the following:

$$D_t = \text{Population} * \text{Liters per Capita}$$

And liters per capita, as was discussed in section 2.4.6, can be seen to be dependent on some factors as well. There is a clear influence of climate on water demand, however since climate is not included in the model, it is not implemented. This also applies to the influence of power outages on water demand. These could be implemented in future research if the exact relationship with demand can be made more explicit. The model does implement a mechanism where, if demand was not met in the previous time step, demand is reduced by 5%. This is attributed to the population's adaptive behavior to conserve water in a societal collapse. It is not typical of a societal collapse, but rather an assumption. It may be possible that people are likely to store/hoard water in times of shortages and intermittency in supply. This would mean an increase in demand if demand was not met in the previous time step. In this model, it is assumed that the demand reduction is a result of reduced usage in other water-intensive activities, such as showering frequently and using washing machines, etc.

Parameter 2: Departure of qualified (technical) personnel
The departure of technical personnel is related to the amount of people that leave at any given time. They are related to the same reasons that people leave, such as frequent blackouts, etc. The performance of the specialized workers depends on several other components in the dependency matrix, which are related to their ability to work effectively within their operations. This causes it to experience disruptions, but it also has an additional disruption due to population decrease. In each time step, if the population has decreased as a result of its dependencies, then the specialized personnel's performance is reduced by 5%. This causes dips in the performance of specialized personnel, as those leave the system. The choice of 5% is arbitrary, to model the potential productivity loss as the workforce diminishes.

Parameter 3: Physical damage to infrastructure
In this scenario element, the implication is that there is damage to the infrastructure. Not due to a natural hazard, but rather as a consequence of mechanisms caused by societal collapse. This damage is inflicted on the distribution infrastructure. As the physical distribution network is outside the scope of the model, there is no way to model how damage is responded to, whether workers are sent to fix these, and whether they are fixed. However, what can be assumed is that to fix the damage, there is a need for workers to be sent to that physical location, through transportation means, with the required equipment to fix it. If the performance of specialized workers and transportation is degrading, it becomes harder to fix the issues, and the performance of the water sector is affected by this. This increase in the dependency coefficient can be interpreted as these components having more effect on the performance of the water sector. If there are not sufficient workers to fix the damage, then their performance will decrease. Same for transportation.

Physical damage to infrastructure is modeled as an increase in the dependence on Specialized Workers and Transportation. This increase in dependence is determined by a damage multiplier, defined in each time step. This damage multiplier follows the Weibull distribution curves.

Parameter 4: Reduced availability of electricity
The reliable production of electricity is a complex process with many dependencies, some of which may be disrupted in a societal collapse scenario, but are not considered when modeling from the perspective of the water sector. These can be related to supply chain issues, energy sources, or specific components. The main assumption is that societal collapse causes disruptions. Disruption is seen as a decrease in performance, as explained in section 3.3.2.

The electricity component is disrupted through a Weibull distribution curve. The energy sector is generally sensitive to disruptions due to its complex infrastructure, interdependencies with other sectors, and the critical role it plays in modern societies. As such, the disruptions to the availability of electricity are immediate after a societal collapse. The sector's ability to recover is highly dependent on the societal collapse scenario. Therefore, this ranges from quick to slow recovery.

Parameter 5: Erosion of the financial sustainability of water companies
In the case of financial sustainability, the effect of the financial and banking sector causing problems is modeled through the disruption of the component of Finance and Banking, which represents the general reliability of banks for money. The financial means of the water sector are modeled as the CapEx (Capital Expenses) and OpEx (Operational Expenses). Each respective component has different dependencies, and different processes dependent on it. They are both affected by the financial state of the model, which is the Financial and Banking component. Through services provided by this component being disrupted due to societal collapse, the OpEx and CapEx are challenged. This attempts to approximate how the effect of a societal collapse may influence the financial reserves of the water sector, as well as their ability to maintain acute operations.

Parameter 6: Reduced availability of components, chemicals, transportation
In this scenario element, the affected components are from the manufacturing sector, both for abstraction and for treatment, chemicals, fuel, and transportation. These are also each affected by their unique Weibull distribution curves which causes their performance to decrease.

The disruptions affecting these components are assumed to range from low to medium in severity, varying by scenario; in some cases, disruptions might be minimal, while in others, they could be more significant. Given the extensive supply chains of these components and the possibility of having multiple suppliers, it is assumed that such components would experience less disruption. The disruption rate for fuel, chemical, and manufacturing components is considered quick, whereas for transportation, it is slow. This slower disruption rate for transportation is attributed to the availability of various alternative means of transport, making it less susceptible to immediate disruption compared to other components. All components are characterized by slow recovery. This prolonged recovery period is due to the assumption that supply chains will remain disrupted for an extended time, as it is likely it is not prioritized or dependent on too many factors to recover effectively.

Parameter 7: (Partial) breakdown of data and communication infrastructure
In this scenario element, the affected component is the Telecommunications component. This component is assumed to be disrupted at a medium to high height. This is because of its high sensitivity to disruptions, similar to the electricity network. This disruption is assumed to occur early and increase quickly due to the high sensitivity to disruptions. Lastly, the recovery ranges from slow to quick as there are a variety of possible scenarios that cause disruptions which could each recover at a different rate.

Parameter 8: Contamination of sources
Finally, the last scenario parameter influences the contamination multiplier. This also follows a Weibull disruption curve. The variable it affects, however, is found in the water model. As mentioned in 3.2, the water that reaches distribution is limited by available clean water. Available clean water is a constant that is multiplied by the contamination multiplier.

The contamination of sources is assumed to occur slowly, as it is caused as a result of societal collapse mechanisms happening over a longer time. Its recovery is also slow, as it requires a lot of time for contaminated sites to naturally rehabilitate. This might also not be easily resolved as it is caused by different, complex, and interacting mechanisms. The height of the contamination can range from low to high, due to the high uncertainty and complexity regarding how the water source is contaminated.

4.1.3 Scenario space

The above scenario parameters lead to the scenario space. As said in section 3.1, the scenario space consists of random values of each parameter within the defined range. These scenarios are applied to the model to test how different societal collapse scenarios lead to different outcomes of the metric variables. There are 10 Weibull curves and three values for population change. To provide an overview, table 4.1 gives a qualitative overview of the Weibull curve shapes. The complete quantitative overview is given in table B.1.

Name	Disruption height	Disruption rate	Recovery rate
Infrastructure damage curve	Low to medium	Slow	Slow
Electricity disruption curve	Medium to high	Quick	Slow to quick
Telecommunications disruption curve	Medium to high	Quick	Slow to quick
Financial and banking disruption curve	Low to high	Medium	Medium
Fuel disruption curve	Low to medium	Quick	Slow
Chemical disruption curve	Low to medium	Quick	Slow
Manufacturing disruption curve	Low to medium	Quick	Slow
Transportation disruption curve	Low to medium	Slow	Slow
Contamination curve	Low to high	Slow	Slow

Table 4.1: Approximate curve configurations

The choice of these different curve shapes is obtained from assuming how the disruptions can be expected to be categorized, in terms of the three ways to adjust the curves. The value of these categories is based on assumptions of how disruptions to that component might take place. There are instances in the scenario space possible where there are very high or very low values for each rate. This variability can allow for certain instances of societal collapse scenarios to take on extreme values.

4.2 Dependency matrix

The dependency coefficients, w_{ij}, in the dependency matrix, determine the workings of the transfer functions, as a result of an explicit modeling choice. Because of this, it is important to thoroughly investigate how sensitive the model is to the determination of these coefficients. In this section, first, the topology of the dependency matrix will be explained and discussed, next the sensitivity of the dependency coefficients will be investigated, and finally, two strategies to gain more insight into what these coefficients might be will be expanded on.

4.2.1 Matrix topology

The matrix topology is determined through logical reasoning based on the context provided in chapter 2. It is also a result of the scoping presented in table 3.1. The reasoning behind this is detailed in the subsequent paragraphs. Each disrupted component has a dependence on itself, so its disrupted performance is also considered when calculating its new performance value, as was explained in section 3.4.

Population As stated previously, the actual population level is determined as well by dependencies. These also have dependency coefficients. The components the population is dependent on are; electricity, telecommunications, financial & banking, and transportation.

Specialized workers Their dependencies are interpreted as what workers need to be able to work effectively. Therefore, they are dependent on themselves, as employees often work in teams. Furthermore, specialized workers are dependent on telecommunications, for the same reason as before, as they are required to contact the office and each other. Finally, they are dependent on transportation, as specialized workers are required to be mobile to be able to reach the facility and fix issues.

Electricity For the generation and continuous supply of energy, electricity requires specialized workers. Electricity is also dependent on fuel as fuel might be required to generate electricity, especially in an emergency setting. Electricity has a dependence on telecommunications monitoring of the grid often goes through telecommunications. Electricity is also dependent on financial and banking for investments and required money for repair of the grid, in cases of emergencies.

Fuel The creation and distribution of fuel also require specialized personnel. Fuel is dependent on telecommunications for effective supply chain management. Financial and banking is also required for investment and maintenance of the supply chain of fuel. Finally, transportation is required to be able to deliver fuel to the desired locations, and thus to maintain the supply chain.

Telecommunications For the maintenance of the telecommunications network, specialized workers are required with expert knowledge of the network. Furthermore, electricity is required to keep the telecommunications running. Although some battery capacity is available, these are not sufficient to keep telecommunications running for extended periods. For investments to maintain the network, financial and banking is required.

Automated processes Automated processes relate only to the automation at the water sector's production facilities and distribution network. Automation relies on specialized workers to maintain functionality, in case there are failures. Some automated processes require an internet connection through telecommunications to sensors or other facilities.

Financial and Banking The finance and banking sector relies on specialized workers who understand the systems it is built on. It is also dependent on electricity, as a lot of money distribution between individuals is dependent on digital transactions. For the same reasons, they are also dependent on telecommunications.

OpEx The operational expenses of the water sector are dependent on the specialized workers who track and understand the workings of the company to allocate expenses. It is also dependent on the state of financial and banking.

CapEx Capital expenses are dependent on the state of the operational expenses. If those are severely lacking, then there are not enough reserves to set aside for capital expenses.

Chemical The chemical industry, specifically for the treatment of drinking water, is dependent on specialized workers for its production and supply chain. Furthermore, electricity is required to produce these chemicals. Telecommunications are required for effective supply chain management. Finances are also required to upkeep an effective supply chain. Finally, transportation is imperative to deliver the required chemicals at the desired locations.

Manufacturing Manufacturing equipment for the abstraction and treatment of drinking water is dependent on specialized workers and electricity for the production of the materials, and telecommunications for an effective supply chain. They are also dependent on finances for the procurement of raw materials and effective management of the supply chain. Finally, they depend on transportation to deliver materials to the desired destination.

Transportation The transportation network consists of road, rail, and air. For effective maintenance of the network, specialized workers are required. Secondly, electricity is required for some forms of transport, such as electric cars and trains. For other forms of transport, there is a dependency on fuel. Telecommunications are required for the effective operation of several transportation modes, such as trains, but also traffic lights, etc. Finally, financial and banking is also required for short and long-term investments.

Abstraction rate The rate for water abstraction is dependent on specialized workers at production facilities to monitor and maintain operations. The abstraction process is also dependent on electricity, as all pumps and machinery rely on electricity to function. Telecommunications is necessary for all communications of the abstraction process that does not go through automated processes or specialized workers. Abstraction is dependent on OpEx and CapEx for the maintenance of operations. It is also dependent on the manufacturing equipment that is needed for the abstraction of water. Finally, abstraction is dependent on transportation, for any other component that may be required.

Treatment rate The treatment rate is dependent on similar components as the abstraction rate, except for an additional dependence on chemicals, which is only required for treatment.

4.2.2 Sensitivity of coefficients

Besides the topology of the matrix, the matrix requires dependency coefficients. Although there exist multiple strategies in quantifying these dependencies, it is important to first investigate whether the value of these dependencies has a large effect on the model outcomes.

To investigate this, a sensitivity analysis is performed by randomly assigning values of 1 to 10 to all established dependencies in the dependency matrix. These values were assigned through Latin Hypercube Sampling (LHS). LHS was developed by McKay (1992) as a near-random sampling technique in a multi-dimensional distribution. This is advantageous considering the high dimensional space of the dependency coefficients, it ensures that sufficient samples are taken for each parameter such that the entire range is sampled (McKay, 1992).

The sensitivity analysis is performed by initiating random curves within the specified ranges for the societal collapse scenario. The results demonstrate the effect of changing the dependencies for a single instance of a societal collapse scenario. To determine whether the dependency coefficients have a large effect, one should evaluate the variability of the curves. The results for four transfer function methods are shown in figure 4.3.

To measure the relative spread of the curves the root mean squared error (RMSE) of each curve is taken from the average curve. The average curve is the mean value of the performance in each time step. The metric can demonstrate how far apart the curves are from each other.

A comparison of the three transfer functions is shown in figure 4.4.

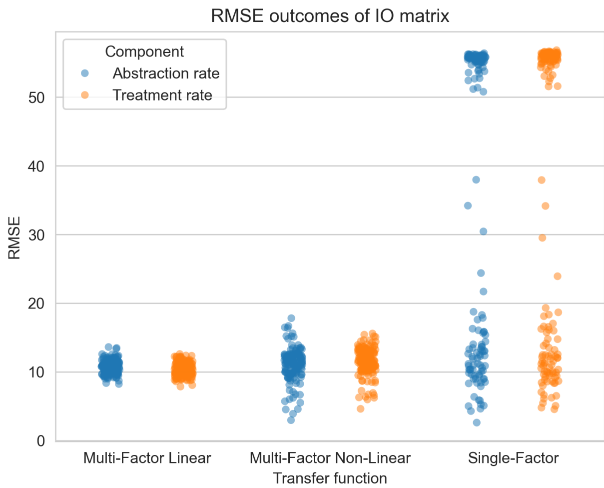


Figure 4.4: Sensitivity of transfer function measured by RMSE

In line with figure 4.3, figure 4.4 shows that the single factor varies the most when testing different values for the dependency coefficients. For many cases, there is a difference of 40% to the average curve. The multi-factor methods are less sensitive to different weights because they account for all the factors, rather than just one. However, there is enough variability in all three methods to conclude that defining these values is important, as different values could lead to differences of up to 20%.

4.2.3 Quantifying dependencies

Resulting from the above, it is worth investigating whether the dependency coefficients can be defined beforehand. In the literature, there are several approaches to quantifying these dependencies. Ouyang (2014) reviews and identifies multiple techniques that modelers use to approach the issue. The most common approach is through an empirical analysis, based on historical data and identifying patterns

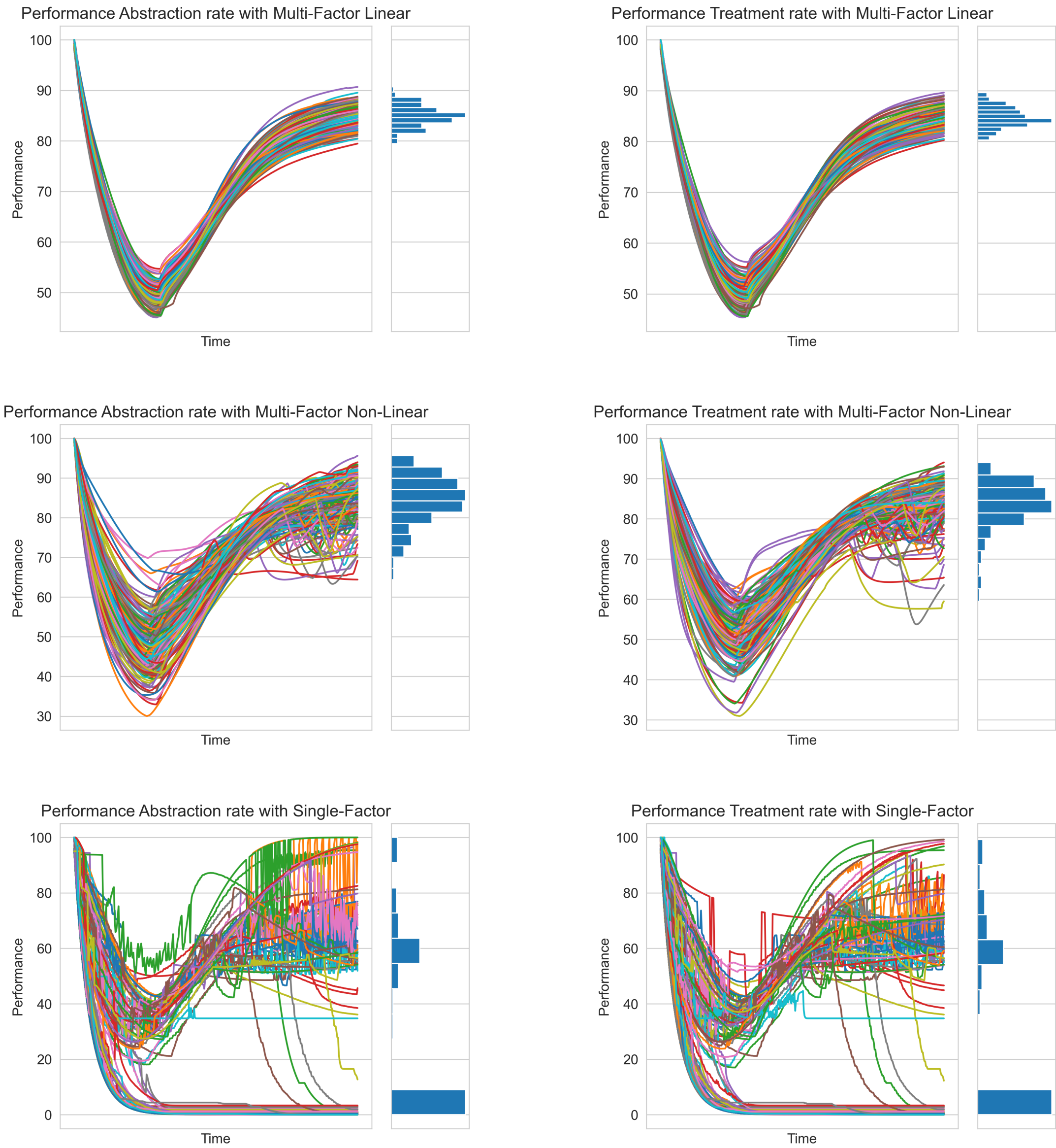


Figure 4.3: Time series outcomes of varying dependency coefficients

(Ouyang, 2014). Setola and De Porcellinis (2008) reflect, however, that to quantify the "true" influence of an infrastructure, one must consider variables like social influence, political consequences, technological implications, etc. It requires large amounts of descriptive data from each infrastructure, and good quality data is difficult to acquire, and can take a lot of time (Santella, Steinberg, & Parks, 2009).

One approach involves interviewing experts and technicians, evaluating the impact on their sector caused by the absence of services provided by other sectors (Setola & De Porcellinis, 2008). However, it is important to consider bias and limitations to expert opinion and acknowledge it is a view of an individual, rather than the empirical truth.

Two approaches that were taken to quantify dependencies for this study were the following:

- Expert interviews: The analysis of the dependencies is determined by experts in the field.
- Input-Output analysis: The analysis of the dependencies is derived from economic exchanges among sectors based on input-output methods in economics.

Expert interviews

During the interviews, the interviewees were asked to rate each sector on a scale of 1 to 10 on how dependent they are on each sector to be able to produce and distribute water. The results are demonstrated through a heatmap in figure 4.5.

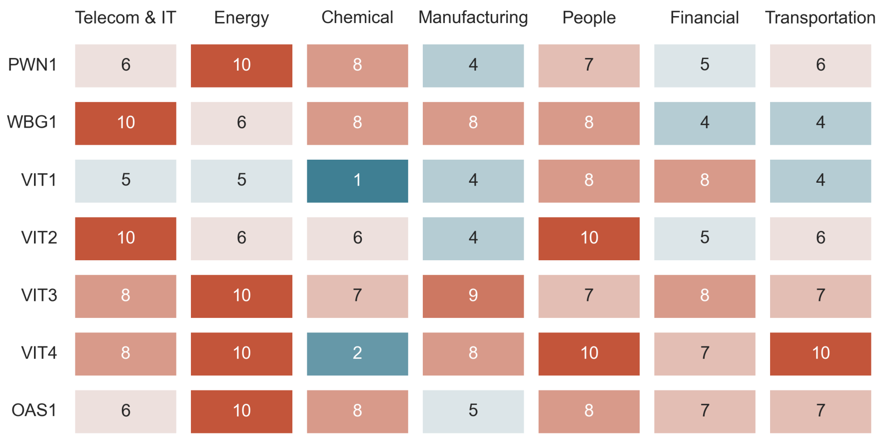


Figure 4.5: Dependency scores by interviewees

Considering the dependency scores, it is interesting to note several clear discrepancies. For example, energy: for 4 of the 7 respondents, the dependency was rated at a 10, however for the other respondents, it was half. In all 7 interviews there was consensus regarding the importance of energy, and how without energy, there is no water. Those specific 3 respondents, WBG1, VIT1, and VIT2 rated this lower, because of the redundancy measures of emergency generators. They argue that this dependence has been mitigated, and therefore they are no longer as dependent on energy providers. The other respondents consider the dependency on the electricity itself, not the providers pointing out that the need for emergency generators indicates that there is a high dependence on electricity.

Discrepancies can also be seen in the chemical and manufacturing columns, where half of the respondents rate it very dependent, and the others far less. For the chemical industry, these discrepancies can be attributed to the definition of what is clean, drinking water. If no calcium is allowed, then chemicals are absolutely necessary. If the descaling of the water isn't required, and in a situation where there are no chemicals available, safe drinking water can still be produced, as the calcium level of the source water is not dangerous for consumption (VIT4). For manufacturing, the discrepancy can be attributed to whether it refers to the need for new materials or the utilization of existing ones. It stems from questioning whether the production of water is dependent on the machines that exist or on the delivery of new machinery.

VIT4 has a high score for transportation. This is largely due to mentioning how important transport is in the case where the production facility is running on emergency generators. They reflect on the importance of chemical deliveries, but these are not part of the primary process for Vitens.

VIT1 claims a consistently low score for the dependency on Telecommunications & IT and Energy, and this is mostly due to Vitens having taken extensive mitigation measures for both sectors and the low perceived risk of nationwide loss of telecommunications and energy blackouts, which extend for periods longer than 10 days.

Given the above analysis, the finalized dependency matrix for the water sector is shown in figure 4.6. This determined score matrix is in line with the interpretations of the experts and considers the perspective of dependence on these elements for continued, day-to-day operation of the water sector as it operates now. As such, there is a high dependence on chemicals, as descaling is part of continuous efforts. The dependence on electricity is seen as electricity to power the process. The dependence on manufacturing is seen as the requirement of new material if something breaks. The remaining coefficients were derived from average values or extrapolated from interview data.

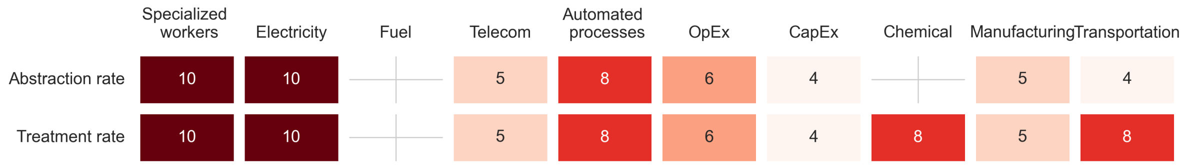


Figure 4.6: Expert dependency scores

Input-output data analysis

An example of the economic theory-based approaches, investigated by Ouyang (2014) is the use of input-output tables. These macroeconomic analyses describe monetary flows from sector to sector and were further developed by Wassily Leontief as a way to analyze backward production flows and the economic dependencies of sectors (Ouyang, 2014). The interdependencies among infrastructure sectors are measured by economic relationships found in the large-scale databases of national input and output tables (Ouyang, 2014). Economic transactions, however, do not entirely demonstrate the complete picture of dependencies. Furthermore, it only demonstrates dependencies on sector level, and not on component level.

To analyze the IO-tables of the Netherlands, input-output tables from 2022 obtained from CBS were used. These contained 80 sectors, which were categorized into the sectors that are relevant to this study. The category subdivision is provided in table B.2 in appendix B. In the IO-table, consumption and salaries are regarded as only an input and output respectively. This means that there is no monetary flow from the workforce to the water sector, and no monetary outflow to consumers. It can be assumed that the people who receive salaries from the water sector also fall under consumers.

Figure 4.7 is a Sankey diagram demonstrating the transaction flows to and from the water sector. Sectors on the left provide monetary input to the water sector, and the water sector in turn provides monetary input to the sectors on the right.

Consumers are the largest source of income for the water sector, which makes sense as household consumers use 70% of the produced drinking water (Baggelaar et al., 2022). It can be stated that for their financial sustainability, the water sector is highly dependent on its consumers to pay for their water. The rest of the sectors have a relatively very low inflow towards the water sector, indicating that

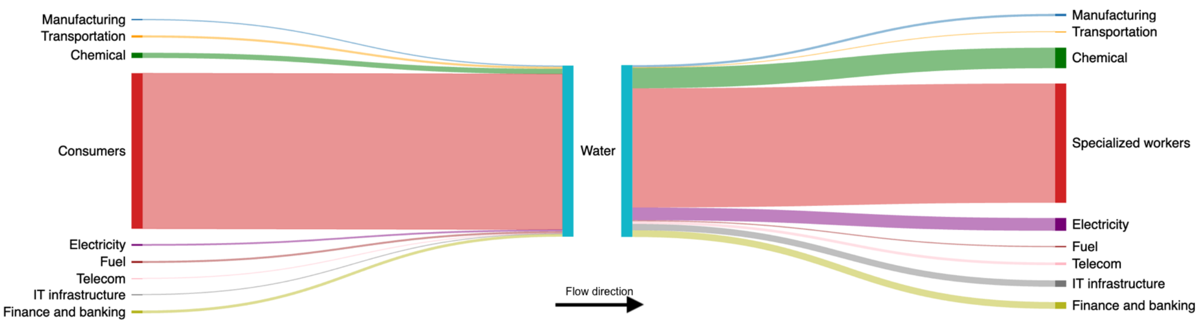


Figure 4.7: Economic flows water sector

drinking water is mostly for consumption rather than operations of other sectors.

Most of the expenses of the water sector are toward the salaries of its employees. Besides this, there is also a relatively high output of the water sector toward chemicals, which makes sense as the water sector purchases chemicals for water treatment. There is also a high relative transaction towards electricity, which indicates the dependence on electricity for the operations of the water sector.

The absolute values of economic transactions pose a challenge when translating to a dependency score. The difference between flows is so vast that some become negligible as a result. To compare the dependencies among the sectors, a two-step normalization process was performed. A standard scaling method adjusted the values so that the mean of the dataset shifted to 0. Under this transformation, a value of 1 corresponds to the maximum observed value, while -1 represents the minimum. The second step was using a min-max scaler, adjusting the data to fit between 0 and 1, with 1 representing the highest value and 0 the lowest. This was then multiplied by 10 to obtain a score as these are defined in the dependency matrix. This two-step normalization process facilitates a more nuanced comparison of sector dependencies by standardizing the data. The second step is mostly performed to increase interpretability. The outcome was the following dependency matrix, shown in figure 4.8. A dependency is seen as a row component paying for services from the column component.

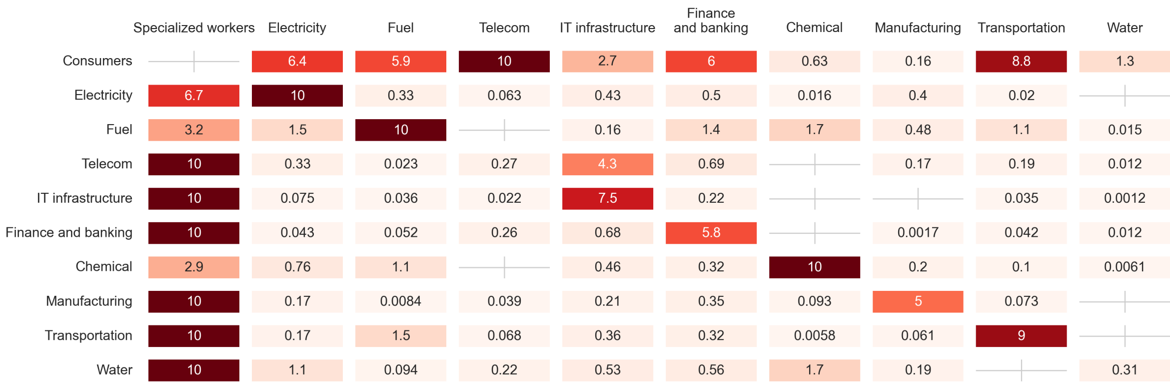


Figure 4.8: Heatmap economic dependency

Specialized workers do not spend their own money on the things they are dependent on to work, the sector they work for spends it for them. Therefore it is not possible to identify dependencies within a sector's operations. As stated by Setola and De Porcellinis (2008), simply looking at economic flows cannot provide a complete image of all the dependencies, but it can help to understand possible topologies and relationships.

The figure shows that all sectors are highly dependent on specialized workers. A lot of money is spent on the salaries of employees. Furthermore, there are consistently high dependencies on the diagonal, signifying a high dependence on own production for more economic output. The sector is highly self-sufficient, serving as both a major supplier and a major consumer of its products or services.

There is a relatively low interdependence across sectors, as most of the scores are << 1. The dependency matrix is much sparser when only considering financial transactions.

4.3 Adaptation in dynamic dependence

An important concept in resilience, as described in section 2.3.3, is the ability of the water sector to adapt. In this research, adaptation specifically relates to a sector's ability to change its dependencies, as a response to a dependent component performing less favorably.

To allow for this, there is a notion of dynamic dependencies. As the name states, it refers to the possibility of changing the dependencies for a specific component. These can be explicit examples where redundancy measures are implemented that allow for a sector to be able to dynamically change its dependencies. It can also occur in the form of adaptation, where a sector can boost its recovery by temporarily, or even permanently, changing its dependencies to increase its performance. An example of an adaptation that explicitly changes the dependency topology is the use of emergency generators. Although a short-term measure it allows the water sector to continue producing water despite a lack of electricity supply.

The implementation of a dynamic dependency can lead to the following changes. A combination of both is also possible. The ability to adapt is only available to the water sector. A change in dependency thus only applies to the components: treatment rate and abstraction rate.

Topological change A topological change refers to a change of dependencies such that dependencies that were previously 0 now obtain a value (between 1 and 10), meaning that a new dependence is created. It also goes the other way, where a dependence that has a value is overwritten to be 0.

Quantitative change A quantitative change refers to a change in the weights or dependency coefficients assigned to existing dependencies. It can increase or decrease.

In the model, the water sector is given three strategies by which it can increase its performance, should the new set of dependencies allow it to. The water sector uses all 4 dependency matrices to calculate its new performance. The dependencies that obtain the highest combined performance of treatment and abstraction rate are chosen. The strategy that was chosen is then recorded. The water sector can change its dependencies in every time step.

4.3.1 Strategy 1: Emergency generators

The use of emergency generators is inherently short-term. The advantage is that it removes all dependency on electricity and instead creates a dependency on fuel and transportation. That is because generators require fuel to function, and transportation needs to be able to get the fuel at the facility in the first place.

Implementing the availability of an emergency generator leads to a topological change as well as a quantitative change. The new dependency scores are given in figure 4.9.

	Specialized workers	Electricity	Fuel	Telecom	Automated processes	OpEx	CapEx	Chemical	Manufacturing	Transportation
Abstraction rate	10		10	5	8	6	4		5	10
Treatment rate	10		10	5	8	6	4	8	5	10

Figure 4.9: Strategy 1 dependency scores

As can be seen in the figure, the score for electricity has become zero, and the score for fuel and transportation a 10. This is to highlight the need for fuel and transportation when using emergency generators. It makes the option less attractive if either component is performing badly.

4.3.2 Strategy 2: Reduced water quality

As many interviewees stated, in the Netherlands, the treatment of water to remove calcium is not a necessity for the quality of the water. In emergencies, where there is no more supply of chemicals, the quality of the water without descaling is safe for drinking. As a result, an adaptation strategy available to the water sector is the removing of the descaling step in the process, and delivering drinking water with a higher calcium concentration. In scenarios where the supply of chemicals is highly disrupted, such a strategy may prove useful and could improve performance.

	Specialized workers	Electricity	Fuel	Telecom	Automated processes	OpEx	CapEx	Chemical	Manufacturing	Transportation
Abstraction rate	10	10		5	8	6	4		5	4
Treatment rate	10	10		5	8	6	4		5	4

Figure 4.10: Strategy 2 dependency scores

It results in the disappearance of the dependence on chemicals, and a decreased dependence on transportation, as transportation is mostly for delivering chemicals.

4.3.3 Strategy 3: Combined emergency generators and electricity

Given that a time step is mostly arbitrary, the water sector may decide to combine emergency generators and electricity. A combination might prove more useful than switching entirely to emergency generators. It is a relevant strategy in the case of an enduring situation of intermittent supply of electricity.

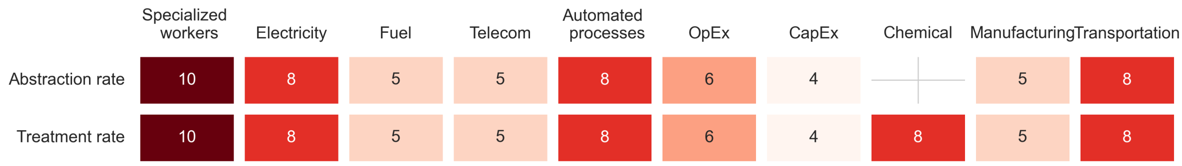


Figure 4.11: Strategy 3 dependency scores

The dependence on electricity is slightly less, but there is an increased dependence on fuel and transportation, however not as much as for strategy 1.

4.4 Main points chapter 4

- The scenario elements are translated into scenario parameters by implementing disruptions. The disruptions are modeled as Weibull distribution curves because of the ease of tweaking these to the desired shape.
- Demand is modeled as population multiplied by liters per capita. It is an aggregated demand, based on average liters per capita.
- Damage is modeled as an increase in the dependency on specialized workers and transportation, as it is assumed that these will be required to fix damages to the network.
- The dependency matrix is determined through logical reasoning and input from chapter 2. It results in 40 dependency coefficients for 15 dependent components.
- The values of these dependencies have a high effect on the model, especially in the Single-Factor approach, as it determines the pathway of cascading failures. Because of this, it is important to define these dependencies to closely represent reality.
- Quantifying these dependencies is not easy. It can be done in multiple ways, with some better than others, but none fully correct. Two ways to do this are through expert interviews and input-output analysis.
  - The expert interviews provide a good insight into the dependencies from the perspectives of the experts but can lead to high discrepancies. These discrepancies are mostly a result of interpretation differences by experts at different levels.
  - The input-output analysis provides some insight into economic dependencies, but the value of the analysis is limited. Many dependencies are often not expressed in economic terms, such as physical dependencies. Also, the absolute values vary widely, making comparison difficult.
- To allow for adaptation strategies, the model also accounts for the existence of emergency generators at the water sector level, which leads to a change in dependencies. This is one of the three strategies the water sector has to try and maximize its performance.

5 | Model Analysis

In this chapter, the model is analyzed for use. This section explores three experiments that were performed using 500 randomly generated scenarios. The chapter analyzes how the model responds to different inputs, from chapter 4, and reflects on how modeling choices can lead to certain outcomes. The chapter aims to provide insight into how the model works and what observations can be made.

5.1 Experimental set up

To analyze how the different inputs lead to different outcomes, and to gain a better understanding of what the model is capable of, three distinct experiments are carried out. Firstly, the model was run using the dependency matrix as defined by the expert interviews and the background research. For the first experiment, the aim is to investigate whether defining the dependency coefficients is required for the interpretation of the model. The second looks into the use of the Input-Output table as a dependency matrix and investigates how this differs from using the expert-informed dependency matrix. Finally, the third experiment investigated how the use of adaptation affects the outcomes, and whether this improves performance.

For these experiments, 500 scenarios are generated by which to analyze the model behavior. A single scenario can be seen as a randomly sampled set of uncertainty levers. The sampling is done through Latin Hypercube Sampling (LHS), which is a near-random sampling technique that ensures sufficient samples are taken for each parameter so that the entire range is sampled (McKay, 1992).

As the model is deterministic, a single simulation run is enough to produce an outcome. The random activation of the sectors is fixed with a random seed. A sensitivity test on the effect of random activation reveals that it does not influence the outcomes of the model. Thus, a single simulation run is needed. The outcomes of a simulation run are the response of the abstraction rate and treatment rate to the disruptions of all interdependent sectors. Each line represents the response of the component to a unique set of disruption curves and population changes.

The analysis of the outcomes will involve examining the time series data to observe trends and patterns over time. To complement this analysis and provide another visualization of the data, the Root Mean Square Error (RMSE) metric is used. The RMSE is calculated by taking the square root of the mean squared error. The mean squared error, in turn, is determined by averaging the squares of the errors, which, in this context, are the differences between the maximum performance level of 100% and the observed performance values at each point in time. A high RMSE value suggests that, on average, the performance levels are far from 100%, indicating a lower average performance. This metric helps quantify the extent to which the performance deviates from the maximum, providing a numerical indicator of the component's overall disruptions.

Experiment 1

The first experiment is set up to test the sensitivity of the dependency matrix. Having established that the dependency matrix can influence model behavior, it is worthwhile to investigate whether a close-to-reality dependency matrix responds similarly to the disruption curves compared to an entirely random matrix. There are two random matrices, which are compared with the expert matrix. The random matrices have randomly generated values for each of the dependencies. For all three matrices, the dependencies of each component are consistent. this means that the structural layout, or topology, is identical across all three matrices. The network of connections between components is the same. Only the values of the dependencies are different.

The expert matrix is defined and defended in Appendix B, in table B.3, with dependencies for the water sector as shown in figure 4.6. Adaptation strategies are not available for this experiment.

To measure the difference between the expert matrix and the two randomly defined matrices, the curves for a single scenario will be compared using the Mean Signed Difference (MSD) between the expert matrix and each random matrix individually. The MSD takes the average of the difference between the two curves such that a positive number means the new curve improved compared to the expert matrix, and vice versa. The MSD will be calculated separately for each matrix to determine how closely each random matrix produces the outcome to the outcome of the expert matrix. If this value is close to zero, it means there is a high similarity between these curves. If the values are consistently close to zero, it would signify that there is not much difference in a single response and that the value of the dependency coefficients does not have an effect. However, based on previous findings in 4.2.2, it is likely that these MSD values will not be zero.

What is also interesting to investigate is whether in all cases, the worst-performing curves (measured by the RMSE) are consistent across the three dependency matrices. This would give insight into the role of the dependency matrix in causing cascading failures. If these are very inconsistent it would indicate that the dependency matrix values play a large role in causing these.

Experiment 2
In the second experiment, the values from the Input-Output table are used, based on the analysis of section 4.2.3. These indicate financial transactions as dependencies. The IO table will be used as the dependency matrix. In essence, the IO matrix is much sparser, compared to the expert matrix, which might lead to fewer cascading failures. The outcome of the experiments could be seen as the economic losses leading to a degradation of performance, and no other dependency.

As with the first experiment, the outcomes derived from these scenarios will be compared to the outcomes of using the expert matrix. To determine the differences in outcomes, specifically when focusing only on economic flows, the MSD will be calculated between both outcomes. The comparison can help to ascertain the extent to which these diverge under the consideration of economic dependencies as opposed to more types of dependencies.

Experiment 3
The third experiment will take the expert matrix, and compare the effect of adaptation strategies over not having adaptation strategies. These will be investigated whether indeed they improve the performance of each component over time. In addition, to investigate how adaptation strategies aid the water sector, the strategies will be further examined. Firstly by investigating the frequency that a strategy is chosen, and finally, by investigating which strategy is dominant over which time step.

5.2 Investigation of expert matrix results

To analyze the effects of the scenarios, the experiment using the expert matrix on the 500 scenarios is demonstrated. In this section, the difference between the transfer functions is observed and analyzed.

5.2.1 Time series outcome

The plotted time series of all outcomes split per transfer function and component is shown in figure 5.1.

An interesting phenomenon of the single-factor approach is that in a large number of cases, the single factor leads to a total collapse – performance reaches zero, and never recovers. This artifact emerges from the mathematical approach used to devise this transfer function. As a component is affected only by the worst-performing component, this component is likely to pull the performance down to zero. As this effect is felt by all the interconnected components, the fact that a single component reaches zero will lead to all the components dependent on it reaching zero. When interpreting the single-factor approach as the component becoming a bottleneck in operations, it could be said that the failure of a bottleneck component is enough to halt all possible functionality of another component. Then a total collapse of the water sector is not that unlikely. However, the single-factor approach doesn't differentiate a badly-performing component from a bottleneck component. Therefore, the function is too overpowered and leads to a complete collapse in the great majority of cases.

The single-factor transfer function in the cases where there is no collapse shows a high level of chaos. Lines fluctuate extremely and it becomes very difficult to interpret the outcomes by looking at the curves. It demonstrates furthermore the high sensitivity of the approach to the dependency matrix and the scenario curves.

In both the multi-factor linear and non-linear approaches, the distribution of the endpoints on the curves tends to form a pattern that resembles a normal distribution. This outcome occurs despite the LHS technique for data sampling. Essentially, these endpoints are the result of computing the weighted average of a set of randomly selected performance percentages. Such averages naturally gravitate towards a central value, a phenomenon explained by the central limit theorem. This theorem states that the average of a large number of independent random values will approximate a normal

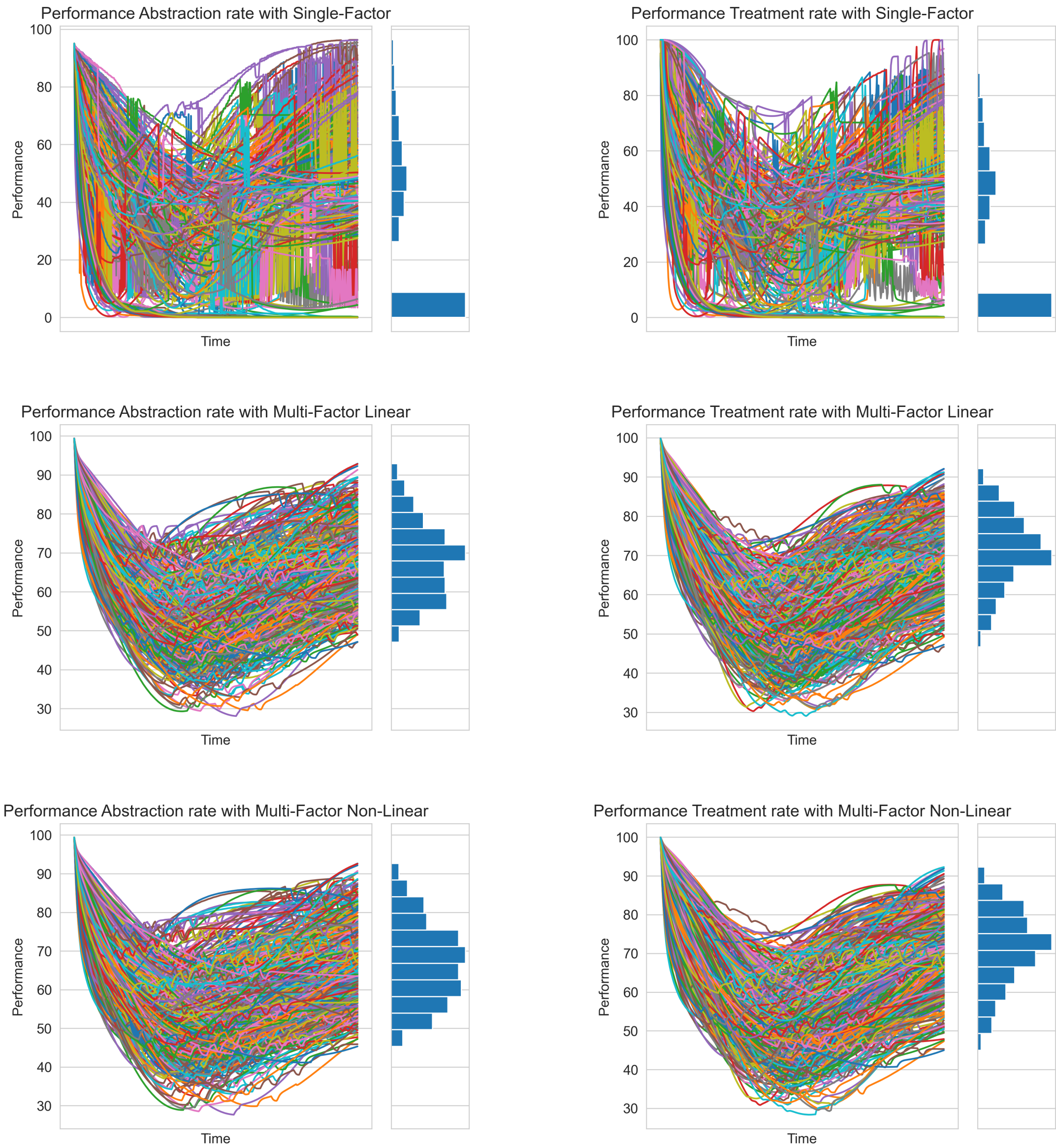


Figure 5.1: Time series outcomes

distribution, regardless of the original distribution of these values. Consequently, the observed average performance level tends to stabilize around 70%. This indicates that the average performance at the end of a simulation is around 70%.

The spread for the multi-factor linear is slightly less than for the non-linear, where the non-linear abstraction rate has a skew towards the lower end. For non-linear, this would make sense if badly performing components have a higher weight in the dependency matrix. Then that higher weight tends to pull the performance down more. For the treatment rate, the skew is towards the upper end. This is likely because the treatment rate has more dependencies and therefore a higher chance of being able to increase its performance at the end.

In the curves, slight oscillations can be seen in both linear and non-linear approaches. These oscillations result from the 5% drop in specialized workers' performance, as a consequence of the implementation of scenario parameter 2. This was modeled as a 5% dip in the performance of the specialized workers if there was a population decline in that time step. The change is most significant in the performance level of specialized workers but is smooth in the abstraction and treatment performances. This is because of the delayed effects of these dips. Essentially, the oscillations show how performance dips and recovers, due to specialized workers leaving the system along with the population in the area. These improve again once the other sectors start to recover. The dips are abrupt and often because the population in the system is sensitive to performance changes. Each population change results in a consistent 5% reduction in performance, irrespective of the size of this change. As such, in some scenarios, the dips are frequent which results in the observed oscillations.

5.2.2 RMSE outcome

Investigating the RMSE-scores of the curves gives insight into the spread. It demonstrates similar effects as were seen in the histograms of the time series outcomes.

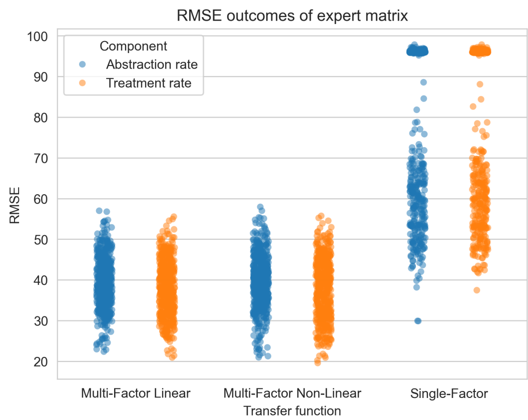


Figure 5.2: RMSE of curves by transfer function

A similar spread of the points can be seen, where the single-factor approach on average performs much worse than the other two. In this visualization, no big differences can be noted between the distribution and the values of the linear and non-linear multi-factor approaches. There are also no big differences between the spread for either component. The same scenarios appear when investigating the top and bottom 10% of the RMSE values. This indicates that there is not much variation when using linear or non-linear. Investigating further showed that on average, the performance value differs by 2% when using the non-linear approach instead of the linear approach.

To investigate whether the scenarios that cause a collapse in the single-factor approach lead to lower performance in general for the other two approaches, the scenarios for which the single-factor approach fails are highlighted. The results are shown in figure 5.3.

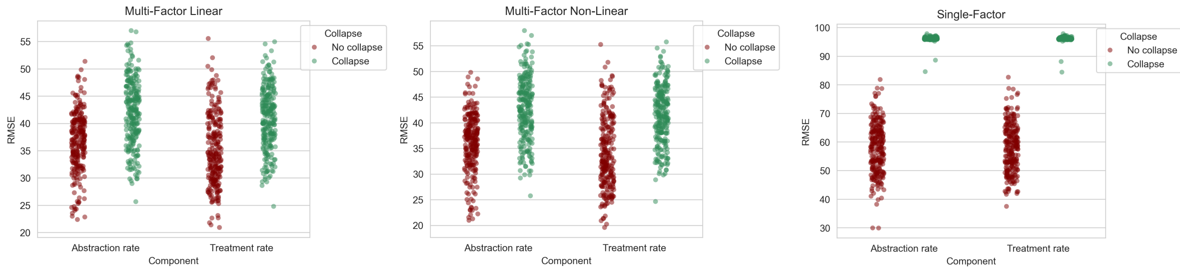


Figure 5.3: SF collapsing across transfer functions

The figure shows that the distribution of points where the single-factor collapsed is slightly higher, but not a lot. It shows that, to some extent, it can be said that in cases where the single-factor collapses, the scenario input often leads to a higher RMSE, which is a generally lower performance score. It further confirms that the single-factor approach collapses, even in scenarios that lead to generally good outcomes in the multi-factor approaches. The sensitivity to the disruption curves is too high.

5.3 Experiment 1: Dependency matrices

In this experiment, the same scenarios were tested with two new input matrices, which were then compared to the outcomes from the expert-defined matrix. Although all matrices share the same structure, the new ones have randomly generated values for dependency coefficients. To assess any significant differences in outcomes, the Mean Signed Difference (MSD) is calculated for each new matrix against the expert matrix. The MSD measures the average difference between the outcome curves, by subtracting the outcomes from the random matrices (1a and 1b) from those of the expert matrix in each time step and calculating the mean. The resulting MSD is a value that indicates how much difference there is between the performance values in each time step. A positive MSD means that the new dependency matrix leads to an on average better performance than when using the expert matrix. A negative MSD means on average worse performance.

For this experiment, it is specifically interesting to consider the value of the MSD. If the value is close to 0, this indicates that there is little difference between the outcomes. This would indicate that the randomly generated matrix and the expert matrix result in similar outcomes for the same given scenario. If the value is far from 0, this would indicate that there is, on average, a large difference between the time series outcomes of the inputs.

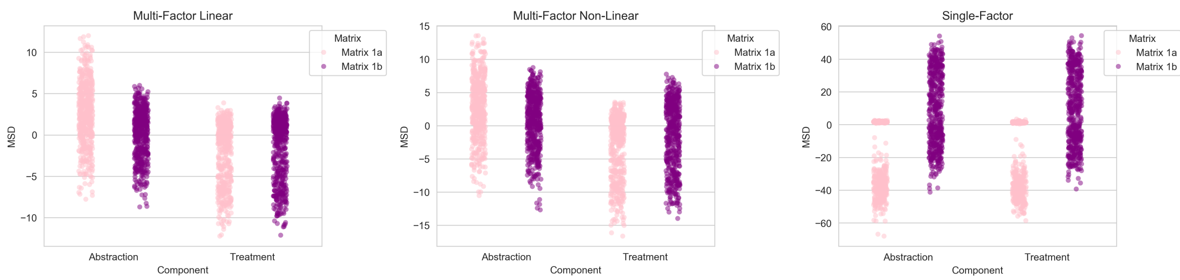


Figure 5.4: Experiment 1: MSD difference expert matrix

In figure 5.4 the MSDs for matrix 1a and matrix 1b are shown. For the multi-factor approaches, it can be seen that there is a difference between curves of the same scenario. Both matrices center around 0, matrix 1a ranges from 15 to -10, indicating generally slightly better performance, whereas matrix 1b ranges around 10 to -10, showing no explicit improvement. The single-factor approach shows a huge variation in MSD, signifying a high variability and sensitivity to the dependency matrix.

To investigate whether randomly defined matrices lead to different responses to the same scenario, the top and bottom 10% of the RMSE from the expert matrix were compared. For the 50 lowest RMSE cases for the expert matrix, there is minimal overlap across the expert matrix, matrix a, and matrix b. There are only 10 common scenarios, of which most are in the multi-factor linear approaches. There are no discernible visual similarities between the disruption curves for these 10 scenarios. For the single-factor approach, there were little to no overlapping scenarios in best-performing or worst-performing cases. This is likely because of the collapsing phenomenon, as matrix 1a saw all single-factor scenarios collapsing. Even in a milder scenario, the single-factor approach causes a total collapse.

In the investigation of the use of a random dependency matrix and using the expert matrix, it is clear that it makes a difference. This outcome was expected, as the transfer functions rely heavily on the weights within the matrix to determine the new performance. To be able to interpret the outcomes, the matrix should closely represent reality.

5.4 Experiment 2: Input-Output tables

When using Input-Output (IO) tables as the input for the dependency matrix, a dependence means that a financial transaction is required to produce output. As such, a component is only able to perform at 100%, if the components it pays for, and thus depends on, are performing at 100%.

The resulting time series curves for the performance and abstraction rate are shown in figure C.1 in the appendix. The RMSE outcomes are displayed in figure 5.5 which summarizes the curves.

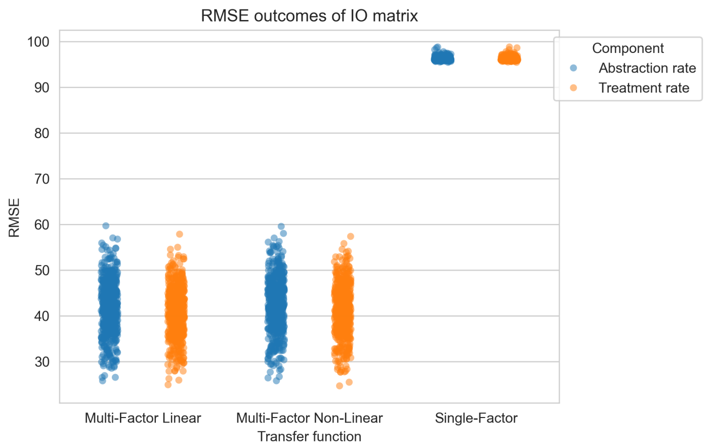


Figure 5.5: RMSE of curves by transfer function

In this set of dependencies, the single-factor approach collapses in all instances. It demonstrates that the set of dependencies is not enough to allow the sector to recover. This is likely due to the sparseness of the IO-matrix, with often only one or two components having a high dependency. In such instances, if one of those components experiences high disruption, the effect is strengthened throughout the network. The single-factor approach proves once again too powerful.

In the multi-factor approaches, similar behavior as with the expert matrix is observed. There is a normal distribution visible at the endpoints of the curve. The RMSEs are also very similar for both multi-factor approaches.

Considering this approach, it is interesting to compare whether, for a single scenario, the curves are very different from the expert matrix. With the same method as for experiment 1, this is measured by calculating the MSD for the expert matrix curve to the IO matrix curve. The results are shown in figure 5.6

For the multi-factor approaches, the MSD is centered around 0 and ranges towards -20. This indicates that the IO matrix performs similar or lower in all cases. It reinforces that the topological differences between these two approaches play a large role in how societal collapse may affect these. The consistently lower performance indicates that having fewer dependencies, which requires a sparser matrix, is less advantageous for increasing performance. This is due to a lower range of performances to use to increase own performance. The multi-factor approaches benefit from more dependencies as they give more opportunities for recovery, despite having less risk of cascading failures.

For single-factor, this graph shows that the IO matrix leads to a much lower performance for many scenarios. This is because the IO matrix caused a collapse in all cases. As such, the points with an MSD of -70 indicate a scenario where, with the expert matrix, the performance of the component is high, but with the IO matrix collapsed. The outcomes cannot be interpreted as the single-factor approach remains too powerful and consistently causes a collapse with a sparser dependency matrix.

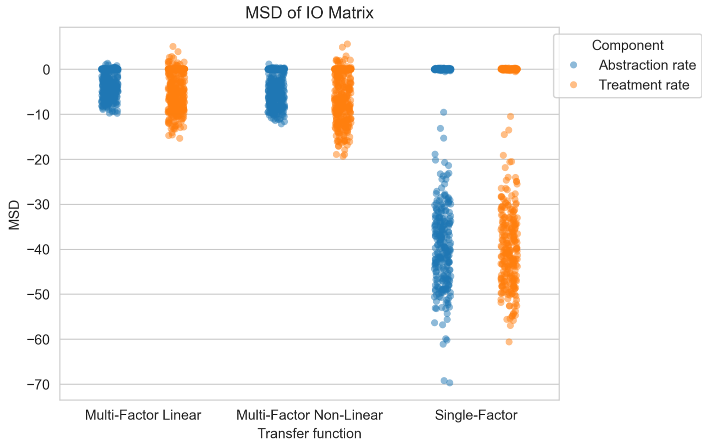


Figure 5.6: Experiment 2: MSD difference expert matrix

5.5 Experiment 3: Adaptation

The third experiment makes use of the expert matrix, with adaptation strategies available. In each time step, the water sector can change its dependencies according to the strategies explained in 4.3. The chosen strategy is the one that maximizes the combined performance of the treatment and abstraction rate. The resulting time series curves for the performance and abstraction rate are shown in figure C.2 in the appendix. This adaptive ability should lead to higher performance rates when compared to the original curves. This would mean an MSD that is greater than zero.

The calculated MSDs are shown in figure 5.7.

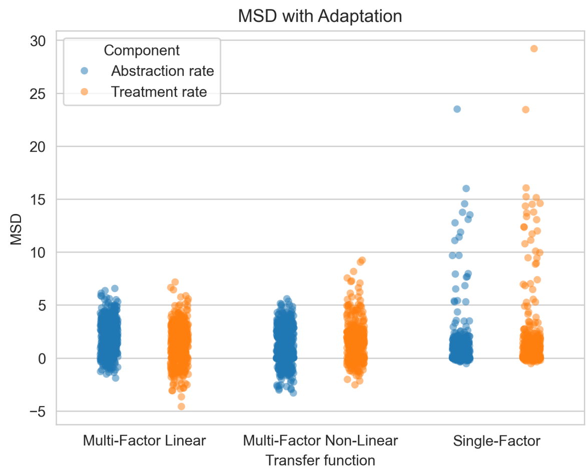


Figure 5.7: Experiment 3: MSD difference adaptation

For both multi-factors, improvement is seen. As expected, most cases are performing better, with the average improvement being up to 10%, compared to no adaptation measure. The multi-factor approach demonstrates that changing dependencies can help to improve overall performance over time, which is the desired outcome. In the single-factor approach, there is similar performance or improvement across all cases. This indicates that strategies for the single-factor approach are very beneficial. This may be due to the adaptation allowing for scenarios that cause a collapse with the expert matrix to improve and not collapse. To investigate this, the collapsed cases can be isolated. This is shown in figure 5.8. The green cluster around 0 indicates that it is not only in the cases where the original matrix did not cause a collapse where improvement was seen. This confirms that the single-factor approach can improve its overall performance well when utilizing adaptation.

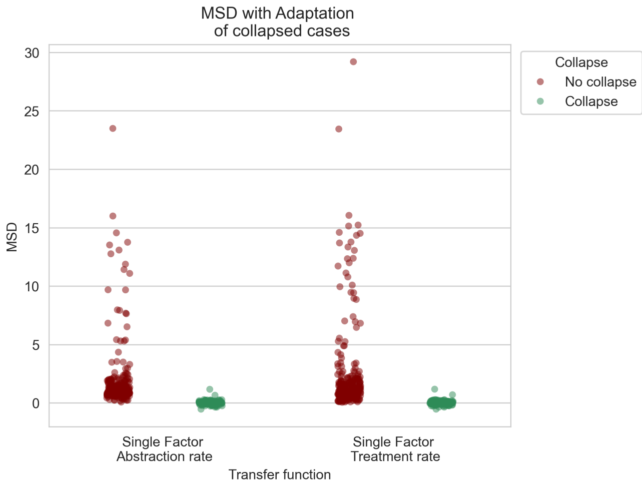


Figure 5.8: MSD difference with Single-Factor collapsing

In some of the scenarios, there was a deterioration in the performance for both the abstraction rate and treatment rate. This can be seen in some of the points having an MSD below zero. To further investigate this, a single scenario can be isolated where this phenomenon is observed. For example, this is demonstrated in scenario 94, shown in figure 5.9, that for abstraction rate, sticking to the normal dependencies would have resulted in better performance, whereas for treatment rate, this would have deteriorated its performance.

It can be seen that the performance for the abstraction rate improves in the adaptation case, whereas the performance for the treatment rate deteriorates. The performance for the treatment rate is higher than abstraction, which would cause the optimization to be in favor of the performance of the abstraction rate, as it results in a higher overall score. The combined performance of abstraction and treatment rate would be higher than without adaptation.

This indicates that having adaptation strategies leads to a better overall performance, whereas sticking to normal dependencies may have led to a better individual performance, but a worse combined performance.

Given that the water sector has to choose the strategy that affects both these components, it would make sense to favor the strategy that boosts overall performance, rather than only the performance of one.

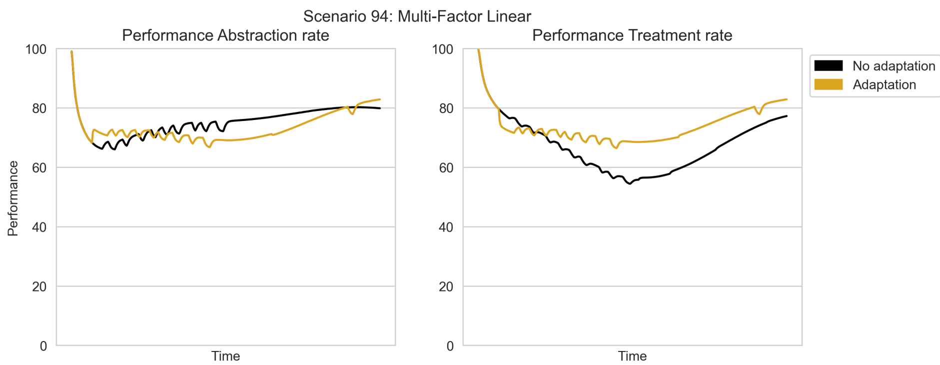


Figure 5.9: Scenario 94

5.5.1 Strategy choices

Having established that switching strategies leads to improvement for each transfer function type, it is interesting to investigate which of the strategies is favored. In each time step, the chosen strategy that obtains the highest performance rate is recorded. The cases where the single-factor approach collapses are excluded from the investigation. This is because, in a situation where all performances give

0 performance, the normal dependencies are automatically chosen. This would give a distorted picture of the effect of the strategies.

Figure 5.10 shows the frequency of each strategy per transfer function type.

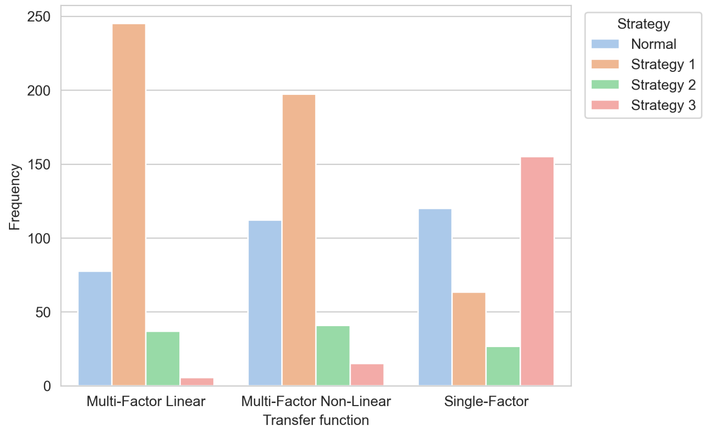


Figure 5.10: Histogram of chosen strategies

Figure 5.11 shows how the choice for which strategy differs per time step per transfer function. The dominant strategy differs for the multi-factor approaches compared to the single-factor approach. The multi-factor approaches favor the first strategy, which is the use of emergency generators. This could mean that the performance of fuel is often better than electricity, and can lead to a better performance when taking the average. For the single factor, the favored strategy is switching to the third strategy, which was a slightly lower dependence on electricity and increased dependence on fuel. The change in weights could affect the size of performance reduction and the choice of the worst-performing component.

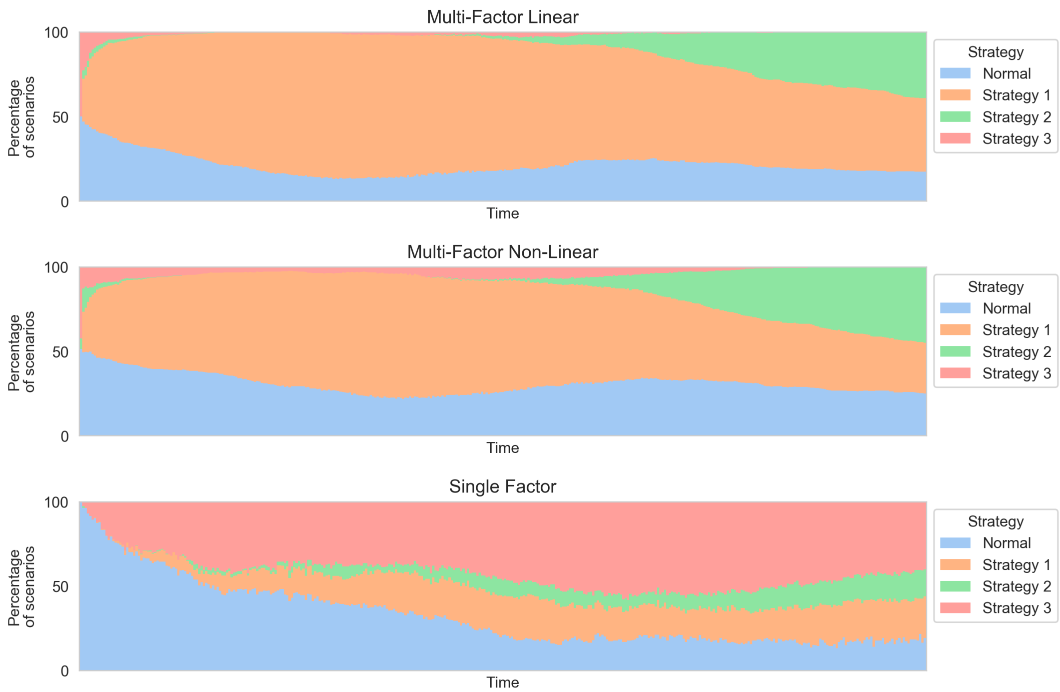


Figure 5.11: Strategy choice over time

The figure gives information into how over time, the dominant strategy changes, that is, the strategy that is most frequently chosen. For the multi-factors, although they both start with the normal dependencies, they quickly switch to a majority for strategy 1, which remains for the continuation of the run, except in the non-linear case, where strategy 2 becomes dominant in the end. This could indicate that the relatively high dependency on chemicals is more debilitating in the non-linear approach in a later phase than the high dependency on electricity. The third strategy is barely relevant for the multi-factor approaches. The dominant strategy of strategy 1 for both multi-factors could indicate that on average, the performance of fuel and transportation is lower than electricity and that removing the dependency on electricity is highly favored by the water sector.

For the single-factor, the third strategy is dominant halfway through the simulation. This shows the same effect that was seen in figure 5.10 and indicates that, when single-factor does not fail, its preference is to have a lower dependency on electricity, as it reduces the performance less.

5.6 Main points chapter 5

- The first step in the model analysis was examining how the expert and literature-informed dependency matrix (the expert matrix) performed against the 500 randomly created scenarios. The single-factor approach performed has a mechanism that caused all performance values to become zero. This is a consequence of how the transfer function is calculated.
- The first experiment compared the influence of using the expert matrix vs. using a randomly defined matrix. It was shown that there was a significant difference in the outcomes, especially for the single factor. This further demonstrated the high sensitivity of the single-factor approach to the dependency matrix. For the other two approaches, a difference between the matrices was clear, indicating the importance of defining the matrix to get interpretable outcomes.
- The second experiment compared the results of the Input-Output (IO) dependency matrix vs. the expert matrix. The IO matrix was sparser, which led to a worse performance for all three approaches. This is because all three approaches benefit from having more dependencies, as it gives more opportunity for recovery, despite giving it more opportunity for cascading failure. It indicated that financial dependencies can impact the performance of a component heavily.
- The third and last experiment analyzed the influence of adaptation strategies on the performance of the water sector. It indicates that adaptation strategies are possible to implement in the model and that the changing of dependencies could increase overall performance for that sector.
- The choices of the strategies were similar for both multi-factor approaches, where the continued use of generators proved more advantageous. For the single-factor approach, the third strategy, which was a combination of electricity from the grid and generators, was more advantageous. This is another consequence of the mathematical set-up of these transfer functions.

6 | Discussion

In this chapter, the findings of chapter 5, as well as the implemented methodology, are discussed. The main questions to answer here are whether this model can sufficiently represent reality, and if it is even fit to offer any real insight into its real-life counterpart. In the discussion, firstly the modeling effort is summarized. Next, the limitations of the approach are discussed, considering how the implementation of certain model elements affects the interpretation. Finally, these limitations will be reflected upon, regarding their implications. It will determine to what extent subquestion 6 can be answered: *How does understanding these responses help to increase the resilience of the water sector to societal collapse?*

6.1 The modeling effort

"All models are wrong, but some are useful." This aphorism rings true for any modeling study. It acknowledges that any created model will always fall short of the complexities of reality. The key is to create models in such a way that they can still be useful.

The model created for this research in no way captures the entire complexities of the system under study. The choices made in defining system boundaries scope the reality that the model depicts. Unquestionably, a model that can accurately represent all relations as they are present in the real world is unfeasible. But that is not the goal. As the quote suggests, models should be useful.

This study aimed to create a model that could effectively capture cascading failures in a network of interconnected components, in the context of a societal collapse. The model was created from the perspective of the drinking water sector, and which components are required for the abstraction, treatment, and distribution of drinking water in the Netherlands. The modeling approach consisted of a System Dynamics (SD) model representing the production of water, which was connected to a larger network model of interdependent components.

The system was studied under simulated scenarios of societal collapse. These simulations included different shapes of disruptions to certain components, defined by the societal collapse scenario elements. These disruptions caused a decrease in performance which affected the performance of other components, finally limiting the water sector in its water production abilities.

The model was analyzed to validate this specific approach and identify what needs attention. By reducing complex processes to simple relationships, where each relationship is governed by mathematical, deterministic rules, is it able to capture similar dynamics in the much more complex real world?

The answer: yes and no. Trade-offs were made in the model between simplicity and complexity, and the key takeaway is whether the simplistic model can capture the complexity of the system. The model can provide an understanding of how being dependent on other sectors can be both useful and not useful. The model can give insights into how more complex domain-specific models can replace modules to create more realistic determinations of performance and more accurate responses to disruptions. The model cannot answer the question of how we can make systems more resilient to societal collapse. Instead, it provides some insights into how cascading failures may affect interdependent sectors.

To understand fully what the model can tell us, the limitations of the approach will be discussed.

6.2 Limitations of model aspects

The modeling approach was to create a network of interconnected submodels that try to mimic the behavior of the system for analysis. The model considered and allowed for a wide range of uncertainties to be tested, which formed possible scenarios for societal collapse. Several elements of the modeling approach have inherent limitations, which will be discussed in this subsection.

Time

The model is explicitly modeled to not be connected to a time dimension. This intentional choice was to avoid interpreting recovery or disruption as being bound to a specific time frame. The response to a drop in performance cannot be said to occur within a specific measure of time. The ticks therefore represent increments in the responses to failures and the translating of these responses to a change in performance. It is more important to consider the sequence of events rather than the actual time it takes for these events to occur. This approach can be beneficial in understanding system behaviors and responses without the complexity introduced by specific timing, which can vary widely in the real world. However, the downside is that it limits the ability of the modeler to use absolute values. A change in population and liters per capita in a time step can differ significantly if a time step represents a day or a month. As such, population change is bounded by time, so it is not entirely possible to remove the meaning of a time step when using absolute values.

Space

The model has no notion of space. Therefore, there is no movement of components from A to B. Having space and movement is integral to understanding what the performance of transportation entails and becomes a challenge when attempting to replace the transportation module with a more complex domain-specific model. The abstraction of transportation to simply a performance metric might omit key properties of the transportation sector.

In addition, there are challenges when considering the pipeline network of the water sector. It is particularly important as one of the societal collapse scenario elements specifically considers the (purposeful) destruction of the network. Along with that, the physical dependencies of the network, such as it being underneath roads or close to cables or gas pipelines, are not explicitly considered.

Despite the limitations, the consideration of space can still be outside the model scope. As societal collapse is not a consequence of natural hazards necessarily, the effects can be modeled without a notion of space. The physical dependencies must be considered implicitly part of the dependency coefficients. Finally, the performance level of transportation must include its capability to deliver required components to the required location without modeling the movement.

Water model

The submodel to represent the production of water was simulated through a System Dynamics (SD) model. SD was chosen because of its suitability in representing stocks and flows. It was suitable for representing the processes of water production without requiring higher-level hydrologic models. These models can more accurately represent water movement but are too detailed for this application. The use of the SD model sufficiently simplified the process. With that, there was no need to acquire data and spatially bind the production facility.

Because of this choice, the water model is limited when trying to accurately model the provision and demand requirements of drinking water. The aggregated flows and stocks do not compare well to more specific requirements of water pressure and quality. Water production is not driven by demand with a certain margin but by pressure requirements. Keeping enough pressure within the system allows users to obtain enough water. Modeling the distribution of water without considering pressure is inherently limited.

Furthermore, the water model does not account for complex climate effects on groundwater levels. These processes cannot accurately be modeled without having a real-life equivalent. Therefore, the groundwater is assumed to be infinite, so the wells are never depleted. This overlooks a crucial phenomenon where water sources might face challenges from demographic shifts and other collapse scenarios. Replacing this module with a more complex climate model, however, requires more data and a location on which to base the information. As a consequence, it adds the challenge of determining climate data. This in itself contains many uncertainties. In addition, the societal collapse scenarios are not explicit on the influence of climate, as the drivers for collapse are outside the model scope. As a result, there are many different conceivable climate scenarios. Adding more uncertainties to the model risks reducing its interpretability. For this model, climate effects were therefore chosen to be excluded.

Demand

Demand is modeled as liters per capita multiplied by the current population, with a margin of 10%. In reality, however, water demand is much more volatile, sensitive to seasons, hours of the day, climate, and many more complex social factors. To model demand so simply severely reduces the complex nature that it has. Therefore, any conclusion regarding the meeting of water demand is limited. For this reason, demand plays a small role in the reduction of performance, only affecting demand in the next time step. Demand does not affect anything else. This simplistic modeling of demand fails to accurately capture how reduced water availability affects people's displacement, inadequately representing the complexities of the real system.

Modeling demand in great detail is unnecessary without an accurate population model and a clear understanding of how people react to societal collapse. It is very difficult to accurately model this, due to the challenge of validating people's responses and the high uncertainty and unique nature of societal collapses. A more detailed population model that integrates human behavior could help to improve the measure of demand. The model would need to capture the dynamics of the population size and how an individual's water demand changes. Such a model will add a lot more assumptions, however, which might reduce the interpretability of the outcomes.

If the purpose of the model is to understand the response of the water sector to disruptions in sectors it depends on, then a simple demand calculation still provides valuable insights, given that demand doesn't have a large influence on the rest of the model. As such, with the current model, the focus should shift away from absolute numbers to prevent overinterpretation of results and instead concentrate on the high-level relationships between water demand and population.

Dependency matrix

The dependency matrix is a simplified approach to determining dependencies between components. A single variable measures the level of dependence of a component on another component. It implicitly encompasses all types of dependencies, physical, geographic, logical, and cyber. It does not differentiate between these types, which is a clear limitation. A component may have a different level of dependence when taking different perspectives. The matrix does not consider all the different ways in which the dependencies might influence the change in a component's performance level.

Determining the topology is integral to obtaining outcomes that can be interpreted. The previous chapter demonstrated in different ways the importance of defining this matrix. It plays a key role in causing cascading failures and aiding recovery. To enhance the interpretability of the model, these dependencies need to accurately reflect the real-life system. However, determining the topology is difficult, as it is different for each individual system. Moreover, since the model is developed from the water sector's viewpoint, it overlooks key sectors that could have a significant influence on other sectors. These are omitted because they do not directly impact the water sector. As a consequence of scoping the number of sectors, there may be many more hidden dependencies that are not being considered and are lost.

Dependencies are also inherently dynamic. This is not only to adapt to changing performance but it could be related to demand fluctuation, where a sector changes its output based on an external factor, and may increase the weight of the dependencies on certain sectors. This could also be the result of weather patterns, or other temporal or seasonal differences, where a component also might change their dependencies to produce a different output. As such, the static dependency matrix as it is defined in the model fails to incorporate these types of dependency changes.

Despite this, models are and should be reductions of reality, with clear system boundaries. In this model, any disruptions caused by sectors outside the model's scope are considered exogenous effects and are implicitly included in the disruption curves.

Dependency coefficients

As well as the topology of the matrix, the value of the coefficients, which represent the strength of the dependence on another component, is very important for determining the mechanisms of the model. As the transfer functions are created in such a way that they consider the weights as a direct and relative effect, the value of these weights is indispensable.

However, chapter 4 already confirmed how difficult it is to determine the interdependence for any given sector. Although expert interviews give very good insights into how interdependencies are experienced by those working in the sector, these are subjective interpretations, and obtaining a complete enough set of respondents is time-consuming. Sending out a survey to gather more information could be a viable approach, but it would be challenging to account for any variations in how the information is interpreted. It is also challenging to select which people are most appropriate to interview. The interviewees are required to have a good extensive knowledge of the specific dependencies of their infrastructure. If they do not know for certain, they might speculate on interdependencies, potentially leading to incomplete and/or inaccurate information. In such cases, logical reasoning might provide the same information.

Transfer functions

The transfer functions are key to the mechanisms of the model. They determine the outcomes that are obtained. As was seen in chapter 5, the three approaches led to very different outcomes. The single factor was very overpowered and led to collapse in 50% of the cases.

The single-factor approach does not distinguish between a bottleneck component that severely limits performance and a component that is performing badly. An extension to the single-factor approach could include defining explicitly what a bottleneck is, but that requires the modeler to have a very good understanding of the dependencies. It also might not prevent the collapse artifact that occurs in the single-factor approach, as a bottleneck component performing badly can still pull down the performance of all interdependent components. The single-factor approach remains too overpowered and does not accurately reflect the effect of interdependencies in reality.

The multi-factor approaches can more effectively account for a shared contribution of dependencies to the failure or recovery of a component. It considers the entire set of dependencies rather than just one bottleneck component. Its limitation is that it does not account for the relative importance of dependencies. Even if all other components are performing poorly, a dependency rated at 1/10 that performs well will still contribute to the improvement of the component's performance. The existence of a bottleneck is not considered by the multi-factor approach. Although it is clear that some dependencies are more important than others, if a bottleneck component collapses, the dependent component can still function. This might not entirely reflect reality, as some functionality can disappear entirely with the loss of a single component.

The non-linear implementation is also limited. Although it attempts to enlarge the relative importance of the dependencies, it still considers each dependency. It is also still a linear calculation taking multiple factors as inputs because it still uses a weighted average. Only the weights are transformed through a non-linear scale. A completely non-linear transfer function, where the calculation of performance occurs through a more complicated function, could result in different behavior. Many other structurally different non-linear functions could be tested to investigate the effect of a non-linear approach.

Essentially, the transfer function is used to simulate a detailed submodel, and how it may respond to a reduced input. The transfer functions should be created in various ways until they can approximate how a component is affected by its inputs, and accurately calculate the new performance level. It would also make sense to implement individual transfer functions for each component, as some may be more sensitive to a bottleneck than others.

Choosing which transfer function is most appropriate to model the system is not possible. It leads to an oversimplification of the problem at hand. Exploring additional transfer functions could be more advantageous for approximating reality. Perhaps a combination of transfer functions, or a unique transfer function per model might be more appropriate. Creating a perfect transfer function that accurately models reality is very difficult. However, trying different approaches and validating the approaches can help to approximate it. Validating transfer functions, however, requires a thorough understanding of the system's real-world behavior and performance under various conditions. It requires comparing the model's output to empirical data or expert assessments to ensure that the results are consistent with the observed phenomena. This information may be gained from exploring detailed domain models that exist to model cascading failures and compare these to real-life instances of disruptions. Alternatively, the transfer functions might be entirely omitted and replaced with a complex domain model that more accurately translates inputs from multiple components into a representation of performance.

Measure of performance

As explained in section 3.3.2, the representation of the performance is explicitly chosen to be flexible, so that it can be implicitly and loosely interpreted. Measuring performance on a 100% scale allows for the ability to mathematically determine how a reduced input leads to a reduced output. In more complex models, it might prove difficult to use a 100%-scale to measure the abstract concept of performance. For example, most energy models model electricity as either on or off, which is challenging to translate to a percentage. Additionally, the interpretation of 100% performance is more difficult for some components than others. Taking the performance of specialized workers as an example: it might be represented by the number of available workers. However, this overlooks the possibility that some workers can temporarily handle additional tasks, or that one worker might compensate for the absence of several others. Aggregating performance to a single continuous scale is challenging and requires the modeler to think explicitly about the significance of a performance level.

For the water sector, its performance corresponds to the percentage of water that can be abstracted and treated. Although this simplifies complex system interactions into an understandable format, it does not fully capture the intricacies of meeting water demand. For example, a water production facility might have minimal operation levels below which it cannot function, translating to a step change in the performance level, rather than a gradual decrease.

Furthermore, the performance measurement overlooks additional metrics like output quality, which could affect subsequent components dependent on this. The model currently assumes that a component's performance indicates that it can only produce a fraction of its normal output, which emphasizes quantity over quality. In other words, it assumes the quality of these outputs remains unchanged. This may not hold true in the aftermath of a societal collapse.

Ultimately, the choice of how to measure performance in each submodel should be aligned with the model's purpose. What decision-making processes is it trying to inform? For example, if it is a matter of deciding which technologies should be adopted to mitigate power outages, the performance value of electricity should be interpretable. It should be robust enough to provide meaningful insights whilst remaining understandable and interoperable with the other modules in the network model.

Societal collapse curves

The impact of disruptions from a societal collapse on interdependent systems and its role in causing cascading failures has not been studied in the literature before. There is no formal definition of the mechanisms through which societal collapse leads to such disruptions, alongside a lack of examples regarding societal collapse affecting modern interconnected infrastructures. Therefore, the modeling of societal collapse is challenging and also difficult to validate.

In this model, the Weibull curves were chosen to represent disruptions to components during a societal collapse scenario. These have a specific shape, with a steep curve to peak disruption and a slow return to zero. An inherent feature of these curves is the possibility of recovery. A curve with intrinsic recovery capability was chosen, originating from the historical observations of societal collapses where societies managed to recover and reform, often evolving into new entities with different operational dynamics. An important consideration is that, if societal collapse automatically leads to recovery, then why should societal collapse effects even be modeled?

The reason for inherent recovery in the disruption curves is to account for the possibility of adapting and restoring performance. Explicitly modeling mitigation tactics to disruptions and the changing of dependencies would allow the modeler to test the resilience of systems under constant decay, rather than disruption curves that recover.

Modeling complete state changes, where a component is disrupted and fails to recover, necessitates models that are capable of adaptation that can boost its performance. Another component might respond to state changes by permanently or temporarily modifying its dependencies. To represent such state changes, disruption curves with an S-curve shape are possible, where components can dynamically change their dependencies to boost recovery. Implementing this approach requires a deeper understanding of the various sectors and their potential for adaptation.

To accurately simulate scenarios where a component experiences a disruption from which it cannot recover, it is essential to have submodels that can adapt to enhance the performance. A component may adjust its dependencies in response to these changes. This would require the modeler to have an extensive understanding of the adaptive capabilities of sectors. These are already difficult to understand or imagine, because of the tendency for infrastructures to resort to redundancies rather than built-in adaptation.

Recovery after a societal collapse may have a completely different form. These can be newly invented forms that are fit for the new, post-societal collapse society. This entails a complete replacement, rather than a recovery of the sector. This new form can have different dependencies, and function in different ways. Infrastructures, with a tendency to adopt technologies and approaches that could be unsustainable in such scenarios, might have to be completely replaced to adapt to societal collapse. It is difficult to imagine what these ways may be, as it is also very dependent on what kinds of disruptions there are. Furthermore, there are not very many opportunities to observe such adaptation in the real world, where dependencies are changed (semi-)permanently.

6.3 Implications of limitations

Given the above limitations, the modeling effort can still be considered useful. The model provided interesting insights into tackling such complex interdependent sectors, and how to model societal collapse. It took a first step into considering the response of infrastructures to long-term sustained pressure, rather than just as a response to temporary disruptions.

The model can serve as a way to query how we are thinking about the problem, rather than providing the answers to the problems it investigates. It can provide tools by which adaptation strategies can be tested and their relative impact on the system. It can help to understand the importance of flexibility in infrastructure planning and design and encourage managers of these infrastructures to consider ways to think beyond redundancy and consider creating opportunities for adaptation.

The ability to adapt to changes should be incorporated in all sectors. The dependency coefficient and the topology of the dependency matrix are static throughout the simulation for all sectors except the water sector. Allowing for flexibility in other sectors' dependencies could improve the model, as the adaptive capacity of these systems is inherent to their complexity. It allows for much more detailed behavior of sectors and their response to disruptions.

Replacing modules with domain models would require the modeler to think about the return on modeling effort explicitly. The central question is whether incorporating more detailed dynamics within a sector can significantly enhance the understanding of how disruptions affect performance. Does it contribute to the model's overall accuracy and validity? Can it effectively replace what the transfer function aims to approximate? But most importantly: can it mitigate the limitations imposed by the current modeling approach?

Integrating an entire sector model requires the modeler to acquire specific domain knowledge. The model also needs to be able to communicate with different models, which may increase the computational requirements. Additionally, it might require obtaining correct data for the model to work, which could be challenging. However, it could provide a more accurate response to societal collapse. The challenge lies in identifying a model that can provide a meaningful interpretation of a reduced input. It should give a performance level that changes when input variables change. Additionally, the model should be able to adapt to these reduced inputs, increasing its performance by switching dependencies or adopting new ways to function. If such a domain model exists, or if such a model can be created, that does not result in inaccurate complex behavior, then it could be worthwhile to replace the module.

7 | Conclusion and recommendations

This final chapter concludes the research with a reflection on the contributions of this research and the recommendations for future research. To start, an overview of the main research findings is presented, which answers the research question. Next, the contributions of this research, to the scientific field and to the water sector are explained. Finally, recommendations for future research are made.

7.1 Overview of the main research findings

This research explored an approach to modeling societal collapse and its effects on interdependent sectors. It was modeled from the perspective of the water sector to investigate how the water supply can be maintained in societal collapse scenarios, considering its complex dependencies. The model was effective in causing cascading failures, but also in encouraging cascading recovery, where if a single component was able to increase its performance, other components could do so as well.

The findings obtained from the research can be used to answer the main research question:

How might the water sector respond to pressures associated with a societal collapse, given its high interdependencies with other sectors?

A societal collapse will undoubtedly cause unprecedented disruptions, but understanding how these disruptions affect the water sector might help to make the water sector more resilient. For example, through incorporating flexibility in interdependencies. The need for flexibility in interdependencies is a key element to consider in the designing of infrastructures. Encouraging the design to be adaptive rather than robust can present good opportunities for resilience in the future. While redundancies can be expensive due to idle components, adaptability might be cheaper in the longer term. Although the initial investment may be great, the potential return on investment, especially in scenarios of long-term disruptions or collapse, could be significant. Implementing RO-filtration, for instance, facilitates adaptation by enabling changes in water source dependency. This approach addresses resilience challenges like groundwater salination or pollution.

7.2 Contributions of this research

This research was conducted as part of an ongoing project in collapsology and deep adaptation. This project aims to consider a new perspective on how resilience should be approached, and which types of issues should be considered. Instead of focusing on improving resilience based on short-term risks, it considers the possibilities of risks that stretch into the long term.

7.2.1 Scientific contributions

There is increased attention to collapsology in the literature, making it integral to study. Although many studies have investigated why past societies collapsed, and other studies have determined that we may be on the verge of a collapse, no study has considered a societal collapse as a given. Many resilience studies, on the water sector, but also many other sectors, have modeled interdependent systems and cascading failures as a result of short-term impacts, but limited on the longer term.

This research contributes to the database of models that exist to understand cascading failures by considering a novel approach. Rather than trying to model the real-life systems as they appear, the model created in this research resulted in a more abstract simulation of the real-life system. By considering components as objects with performance rates and determining a score of how dependent one component is on the other, relatively simple transfer functions already create complex behavior. It can simulate propagating failures without the need for a high level of detail. As a first step, it can encourage future researchers to consider the advantage of a more simplistic approach, which could provide valuable insights.

The methodology can be applied to different case studies, in other countries or for other infrastructures. By first gaining an extensive understanding of the dependency landscape, defining dependency scores in the dependency matrix can be done. Multiple transfer functions can be implemented and tested for their relative importance. If it is deemed to contribute to the accuracy of the model, submodels can be expanded to become more accurate representations of components and their respective performance measures.

7.2.2 Contribution to water sector

Research into collapsology within the water sector seeks to enhance the resilience of water systems against potential societal collapse. It is crucial to explore strategies for maintaining a basic level of water supply, to ensure that today's water infrastructure can withstand such challenges.

Such research has the goal to eventually be integrated into the risk design and operations of water companies in the Netherlands. This would involve embracing flexibility to be able to adapt and increase resilience against societal collapse. It would allow the water sector to fall back on practices that avoid or replace affected links in the dependency web. The research will lead to trying to answer the following questions, on the operational scale:

- How can we enhance the resilience of water systems in the face of long-term societal decline?
- Which current approaches and technologies may prove unsustainable or inadequate in such scenarios?
- Conversely, which current approaches and technologies should be prioritized or reintroduced to ensure continuity?

Ultimately, by examining the water sector through the lens of collapsology this research highlights the importance of taking actions that will promote flexibility and adaptability.

7.3 Recommendations for future research

The investigation done in this report is just the start of a whole new realm of research. There is still so much left to explore and discover about the effects of a societal collapse on modern infrastructures.

This research focused mainly on the perspective of the water sector. The application and outcomes will likely be very different when considering another infrastructure. Investing time to understand these dependencies from the system's perspective, however, incidentally reveals a lot about other systems.

7.3.1 Societal collapse

To further strengthen the study, it would be worthwhile to investigate what could cause a societal collapse and how this might correspond with its consequences. Understanding how the different collapse mechanisms reach a point of no return can help to understand how societal collapses are triggered. Understanding the possible repercussions of a societal collapse can reinforce this. Although it is difficult to validate a scenario, given the uniqueness of a collapse, and the plethora of shapes it may have, it is worthwhile to consider a relevant case study. The issues in Syria of the past decade provide a good example by which to validate findings. It would be very interesting to compare such recent or present-day examples of (local) collapses and attempt to model their dynamics to validate the model.

Another recommendation for future research is to implement any findings from the study of collapse to executable mitigation strategies. Implementing flexibility or understanding how interdependencies pose risks beyond just short-term disasters is an important consideration for the future-proofness of water companies. In addition, investigating how interdependencies have benefits would strengthen the study.

7.3.2 Interdependent systems

For future work, a better understanding of the interdependencies at the appropriate level of abstraction is needed. Therefore, the first recommendation for future study is the use of interviews to understand interdependencies across other sectors. There exist many strategies for identifying dependencies between infrastructures. Though extensively researched in the literature, there is no single approach that works well. Nevertheless, the interviewing of experts in the fields gives invaluable insights into how these interdependencies are observed and considered. For future research regarding the identification of interdependencies, a highly recommended approach is to interview employees at different levels in the company. A very relevant study that devised a methodology for approaching these interviews is in the paper by Setola and De Porcellinis (2008). Applying those methods can give a good, quantitative insight from the experts in the field. Effectively determining a dependency matrix and how this can become dynamic would be valuable for modeling the interdependencies.

Furthermore, a recommendation for future research is in the understanding of benefits that can be gained with the integration of domain-specific models for sector modules. The models might be able to replace the transfer functions, as they could more effectively translate the input to a reduced performance. These models can simulate a closer-to-reality response to changes in input from other sectors. However, it does require obtaining an adequate understanding of the available models, and critically evaluating which level of detail is necessary. Further investigating how to translate a reduced input to a reduced performance for each sector would increase the accuracy of the transfer functions enormously.

Next, a recommendation for future research is to invest time in investigating the possible adaptation strategies that sectors could implement to mitigate the effects of disruptions. Switching operations, or changing the acceptable level of operations are just examples. Perhaps people can be content with a reduced operation of infrastructures in times of crisis. Pushing the boundary of what these possible strategies are can allow for an increase in flexibility for many infrastructures and their operations. Expanding the set of adaptation measures and translating them well into the dependency matrix will improve the model greatly and allow for continuous decay or state changes to be modeled.

References

Agudelo-Vera, C., Mesman, G., Blokker, E., & Adamse, E. (2017). *Drinkwaterverbruik tijdens een grootschalige en langdurige elektriciteitsuitval* (Tech. Rep.). H2O-Online.

Agusdinata, D. B. (2008). *Exploratory modeling and analysis: a promising method to deal with deep uncertainty* (Tech. Rep.). Retrieved from https://www.researchgate.net/publication/27346533

Albergamo, V., Blankert, B., Cornelissen, E. R., Hofs, B., Knibbe, W.-J., van der Meer, W., & de Voogt, P. (2019, 1). Removal of polar organic micropollutants by pilot-scale reverse osmosis drinking water treatment. *Water Research*, *148*, 535–545. doi: 10.1016/j.watres.2018.09.029

Albergamo, V., Escher, B. I., Schymanski, E. L., Helmus, R., Dingemans, M. M. L., Cornelissen, E. R., … de Voogt, P. (2020). Evaluation of reverse osmosis drinking water treatment of riverbank filtrate using bioanalytical tools and non-target screening. *Environmental Science: Water Research & Technology*, *6*(1), 103–116. doi: 10.1039/C9EW00741E

Alifujiang, Y., Abuduwaili, J., Ma, L., Samat, A., & Groll, M. (2017, 12). System Dynamics Modeling of Water Level Variations of Lake Issyk-Kul, Kyrgyzstan. *Water*, *9*(12), 989. doi: 10.3390/w9120989

Baggelaar, P., Kuin, P., & Geudens, P. (2022). *Prognoses drinkwatergebruik in Nederland t/m 2040* (Tech. Rep.). Vewin, PB Icastat en RHDHV.

Balakrishnan, S., & Cassottana, B. (2022, 8). InfraRisk: An open-source simulation platform for resilience analysis in interconnected power–water–transport networks. *Sustainable Cities and Society*, *83*. doi: 10.1016/j.scs.2022.103963

Bandura, I. (2018, 8). *Lines and Circles.*

Bankes, S. (1993, 5). Exploratory Modeling for Policy Analysis. *Operations Research*, *41*(3), 435–449. Retrieved from https://about.jstor.org/terms

Baylis, J., Edmonds, A. J., Grayson, M. E., Murren, J. J., McDonald, J., & Scott, B. (2016, 6). *Water Sector Resilience: Final Report and Recommendations* (Tech. Rep.). National Infrastructure Advisory Council.

Birkett, D. M. (2017). *Articles Water Critical Infrastructure Security and Its Dependencies* (Vol. 8; Tech. Rep. No. 2).

Bologna, M., & Aquino, G. (2020, 5). Deforestation and world population sustainability: a quantitative analysis. *Scientific Reports*, *10*(1), 7631. doi: 10.1038/s41598-020-63657-6

Bolton, L. (2020). Water infrastructure in fragile- and conflict-affected states. *K4D Helpdesk Report*, *912*.

Bos, R., & Merks, C. (2000). Ontharding in korrelreactoren wordt steeds eenvoudiger. *H2O*, 24–25.

Bressman, A., Brown-Rosenbladt, M., Edwards, K., & McGhee, J. (2022, 12). *Understanding Water Treatment Chemical Supply Chains And The Risk Of Disruptions* (Tech. Rep.). Cincinnati: EPA, United States Environmental Protection Agency.

Brozović, D. (2023, 1). Societal collapse: A literature review. *Futures*, *145*. doi: 10.1016/j.futures.2022.103075

Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., … von Winterfeldt, D. (2003, 11). A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities. *Earthquake Spectra*, *19*(4), 733–752. doi: 10.1193/1.1623497

CBS. (2022). *Input-Outputtabellen 2015-2022.* Centraal Bureau van de Statistiek. Retrieved from https://www.cbs.nl/nl-nl/maatwerk/2020/29/aanbod-en-gebruiktabellen-en-input-outputtabellen

CBS. (2023, 11). *Woningen; hoofdverwarmingsinstallaties, regio.* Retrieved from https://www.cbs.nl/nl-nl/cijfers/detail/84948NED

Centers for Disease Control and Prevention. (2020, 9). *Water Disinfection with Chlorine and Chloramine.* Retrieved from https://www.cdc.gov/healthywater/drinking/public/water_disinfection.html

CFI, & Schmidt, J. (2022). *Understanding CapEx vs. OpEx in Corporate Finance.* Retrieved from https://corporatefinanceinstitute.com/resources/accounting/capex-vs-opex/

Chakrabarti, R., Hertz, N., Kabisch, S., Reil, A., & Wolf, T. (2015). Addressing Climate Change Impacts Through Community-Level Water Management: Case Studies from the South-Eastern Coastal Region of India. In (pp. 291–317). doi: 10.1007/978-3-319-10467-6

Champlin, C., Sirenko, M., & Comes, T. (2023, 4). Measuring social resilience in cities: An exploratory spatio-temporal analysis of activity routines in urban spaces during Covid-19. *Cities*, *135*, 104220. doi: 10.1016/j.cities.2023.104220

Cumming, G. S., & Peterson, G. D. (2017, 9). Unifying Research on Social–Ecological Resilience and Collapse. *Trends in Ecology & Evolution*, *32*(9), 695–713. doi: 10.1016/j.tree.2017.06.014

deMenocal, P. B. (2001). Cultural Responses to Climate Change during the Late Holocene. *Science*, *292*(5517), 667–673. Retrieved from http://www.jstor.org/stable/3083536

Drinkwater Platform. (2022). *De organisatievorm van drinkwaterbedrijven.* Retrieved from https://www.drinkwaterplatform.nl/organisatievorm-drinkwaterbedrijf-publiek/

Drinkwaterbesluit. (2011). *De zorg voor de kwaliteit van drinkwater.* Staatssecretaris van Infrastructuur en Milieu.

Dueñas-Osorio, L., & Vemuru, S. M. (2009, 3). Cascading failures in complex infrastructure systems. *Structural Safety*, *31*(2), 157–167. doi: 10.1016/j.strusafe.2008.06.007

D'Agostino, G., Cannata, R., & Rosato, V. (2010). On Modelling of Inter-dependent Network Infrastructures by Extended Leontief Models. In (pp. 1–13). doi: 10.1007/978-3-642-14379-3

European Union. (2022, 12). *Directive (EU) 2022/2557.* Brussels: European Union.

Gillette, J., Fisher, R., Peerenboom, J., & Whitfield, R. (2002). *Analyzing Water/Wastewater Infrastructure Interdependencies* (Tech. Rep.).

Giuliani, M., Anghileri, D., Castelletti, A., Vu, P. N., & Soncini-Sessa, R. (2016, 3). Large storage operations under climate change: expanding uncertainties and evolving tradeoffs. *Environmental Research Letters*, *11*(3), 035009. doi: 10.1088/1748-9326/11/3/035009

Grafius, D. R., Varga, L., & Jude, S. (2020, 12). Infrastructure Interdependencies: Opportunities from Complexity. *Journal of Infrastructure Systems*, *26*(4). doi: 10.1061/(ASCE)IS.1943-555X.0000575

Guidotti, R., Chmielewski, H., Unnikrishnan, V., Gardoni, P., McAllister, T., & van de Lindt, J. (2016, 11). Modeling the resilience of critical infrastructure: the role of network dependencies. *Sustainable and Resilient Infrastructure*, *1*(3-4), 153–168. doi: 10.1080/23789689.2016.1254999

Haimes, Y. Y., Horowitz, B. M., Lambert, J. H., Santos, J. R., Lian, C., & Crowther, K. G. (2005, 6). Inoperability Input-Output Model for Interdependent Infrastructure Sectors. I: Theory and Methodology. *Journal of Infrastructure Systems*, *11*(2), 67–79. doi: 10.1061/(ASCE)1076-0342(2005)11:2(67)

Hanson, R. (2007, 3). *Catastrophe, social collapse, and human extinction* (Tech. Rep.). Retrieved from https://mason.gmu.edu/~rhanson/collapse.pdf

Haug, G. H., Gunther, D., Peterson, L. C., Sigman, D. M., Hughen, K. A., & Aeschlimann, B. (2003, 3). Climate and the Collapse of Maya Civilization. *Science*, *299*(5613), 1731–1735. doi: 10.1126/science.1080444

Hodell, D. A., Curtis, J. H., & Brenner, M. (1995, 6). Possible role of climate in the collapse of Classic Maya civilization. *Nature*, *375*(6530), 391–394. doi: 10.1038/375391a0

Hosseinipour, E., Harris, E., El Nazer, H. A., Mohamed, Y. M., & Davies, P. A. (2023, 11). Desalination by batch reverse osmosis (RO) of brackish groundwater containing sparingly soluble salts. *Desalination*, *566*, 116875. doi: 10.1016/j.desal.2023.116875

IPCC. (2023). *Climate Change 2022 – Impacts, Adaptation and Vulnerability.* Cambridge University Press. doi: 10.1017/9781009325844

Johannesson, P., & Perjons, E. (2014). Research Strategies and Methods. In *An introduction to design science* (pp. 39–73). Cham: Springer International Publishing. doi: 10.1007/978-3-319-10632-8

Johansson, J. (2022, 7). *Cascading impacts and ranking criticality* (Tech. Rep.). VIU Summer School.

Kemp, L. (2019, 2). *Are we on the road to civilisation collapse?* Retrieved from https://www.bbc.com/future/article/20190218-are-we-on-the-road-to-civilisation-collapse

Kemp, L., Xu, C., Depledge, J., Ebi, K. L., Gibbins, G., Kohler, T. A., ... Lenton, T. M. (2022, 8). Climate Endgame: Exploring catastrophic climate change scenarios. *Proceedings of the National Academy of Sciences of the United States of America*, *119*(34). doi: 10.1073/pnas.2108146119

Kennett, D. J., Breitenbach, S. F. M., Aquino, V. V., Asmerom, Y., Awe, J., Baldini, J. U., ... Haug, G. H. (2012, 11). Development and Disintegration of Maya Political Systems in Response to Climate Change. *Science*, *338*(6108), 788–791. doi: 10.1126/science.1226299

Keyhanpour, M. J., Musavi Jahromi, S. H., & Ebrahimi, H. (2021, 6). System dynamics model of sustainable water resources management using the Nexus Water-Food-Energy approach. *Ain Shams Engineering Journal*, *12*(2), 1267–1281. doi: 10.1016/j.asej.2020.07.029

Kim, J., Park, K., Yang, D. R., & Hong, S. (2019, 11). A comprehensive review of energy consumption of seawater reverse osmosis desalination plants. *Applied Energy*, *254*, 113652. doi: 10.1016/j.apenergy.2019.113652

Kloosterman, R. (2020). *Water for now and in the future* (Tech. Rep.). Vitens.

KNMI. (2023, 10). *KNMI'23 klimaat scenario's voor Nederland* (Tech. Rep.). Koninklijk Nederlands Meteorologisch Instituut, Ministerie van Infrastructuur en Waterstaat.

Kohler, T. A., & Rockman, M. (2020, 10). The IPCC: A Primer for Archaeologists. *American Antiquity*, *85*(4), 627–651. doi: 10.1017/aaq.2020.68

Kotir, J. H., Smith, C., Brown, G., Marshall, N., & Johnstone, R. (2016, 12). A system dynamics simulation model for sustainable water resources management and agricultural development in the Volta River Basin, Ghana. *Science of The Total Environment*, *573*, 444–457. doi: 10.1016/j.scitotenv.2016.08.081

Kröger, W., & Nan, C. (2014, 1). Addressing Interdependencies of Complex Technical Networks. *Understanding Complex Systems*, 279–309. doi: 10.1007/978-3-319-03518-5-13

Kronieger, R. (2013). *Noodcommunicatievoorziening* (Tech. Rep.). Ordina.

Kwakkel, J. H. (2017, 10). The Exploratory Modeling Workbench: An open source toolkit for exploratory modeling, scenario discovery, and (multi-objective) robust decision making. *Environmental Modelling & Software*, *96*, 239–250. doi: 10.1016/j.envsoft.2017.06.054

Lawler, A. (2010, 11). Collapse? What Collapse? Societal Change Revisited. *Science*, *330*(6006), 907–909. doi: 10.1126/science.330.6006.907

McKay, M. D. (1992). Latin hypercube sampling as a tool in uncertainty analysis of computer models. In *Proceedings of the 24th conference on winter simulation - wsc '92* (pp. 557–564). New York, New York, USA: ACM Press. doi: 10.1145/167293.167637

Medina-Elizalde, M., & Rohling, E. J. (2012, 2). Collapse of Classic Maya Civilization Related to Modest Reduction in Precipitation. *Science*, *335*(6071), 956–959. doi: 10.1126/science.1216629

Mentges, A., Halekotte, L., Schneider, M., Demmer, T., & Lichte, D. (2023, 10). A resilience glossary shaped by context: Reviewing resilience-related terms for critical infrastructures. *International Journal of Disaster Risk Reduction*, *96*, 103893. doi: 10.1016/j.ijdrr.2023.103893

Ministerie van Economische Zaken en Klimaat. (2022). *Nationaal Crisisplan Elektriciteit* (Tech. Rep.).

Ministerie van Economische Zaken en Klimaat. (2023). *Landelijk Crisisplan Olie* (Tech. Rep.).

Mishra, B., Kumar, P., Saraswat, C., Chakraborty, S., & Gautam, A. (2021, 2). Water Security in a Changing Environment: Concept, Challenges and Solutions. *Water*, *13*(4), 490. doi: 10.3390/w13040490

Nan, C., Sansavini, G., Kröger, W., & Heinimann, H. (2014, 2). A quantitative method for assessing the resilience of infrastructure systems. *PSAM 2014 - Probabilistic Safety Assessment and Management*.

National Coordinator for Counterterrorism and Security. (2023). *Critical Infrastructure (protection).*

Niknam, A., Zare, H. K., Hosseininasab, H., Mostafaeipour, A., & Herrera, M. (2022, 5). A Critical Review of Short-Term Water Demand Forecasting Tools—What Method Should I Use? *Sustainability (Switzerland)*, *14*(9). doi: 10.3390/su14095412

Noordhoff. (2021). *De Grote Bosatlas* (56th ed.). Noordhoff Uitgevers.

NOS. (2024, 2). *Tienduizenden huishoudens in regio Zeist urenlang zonder water.* Retrieved from https://nos.nl/artikel/2508979-tienduizenden-huishoudens-in-regio-zeist-urenlang-zonder-water

Oesterholt, F. (2017, 10). *Industriële en drinkwaterontthardingstechnieken vergeleken.* Retrieved from https://www.kwrwater.nl/actueel/industriele-en-drinkwaterontthardingstechnieken-vergeleken/

Ouyang, M. (2014). *Review on modeling and simulation of interdependent critical infrastructure systems* (Vol. 121). Elsevier Ltd. doi: 10.1016/j.ress.2013.06.040

Patel, S. K., Biesheuvel, P. M., & Elimelech, M. (2021, 5). Energy Consumption of Brackish Water Desalination: Identifying the Sweet Spots for Electrodialysis and Reverse Osmosis. *ACS ES&T Engineering*, *1*(5), 851–864. doi: 10.1021/acsestengg.0c00192

Peñuelas, J., & Nogué, S. (2023, 5). Catastrophic climate change and the collapse of human societies. *National Science Review*, *10*(6). doi: 10.1093/nsr/nwad082

Petersen, K., & Wieltschnig, P. (2020, 12). Balancing Innovation and Vulnerability: Water Security in an Age of Cyber-Warfare. In (pp. 71–82). doi: 10.2495/WP200071

Phan, T. D., Bertone, E., & Stewart, R. A. (2021, 6). Critical review of system dynamics modelling applications for water resources planning and management. *Cleaner Environmental Systems*, *2*, 100031. doi: 10.1016/j.cesys.2021.100031

Phernambucq, I., Mondeel, H., van Loon, A., & Rengers, J. (2019, 11). *Evaluatie beleidsnota drinkwater; bijlage IV* (Tech. Rep.). Witteveen+Bos.

Philip, B., & Aljassmi, H. (2020). The Relevance of Water Pipe Deterioration Prediction Models: A review.. Retrieved from https://api.semanticscholar.org/CorpusID:222128730

Pruyt, E. (2013). *Small System dynamics models for big issues: Triple jump towards real-world complexity.* TU Delft Library.

Pujiastuti, C., Ngatilah, Y., Sumada, K., & Muljani, S. (2018, 1). The effectiveness of sodium hydroxide (NaOH) and sodium carbonate (Na ¡sub¿2¡/sub¿ CO ¡sub¿3¡/sub¿) on the impurities removal of saturated salt solution. *Journal of Physics: Conference Series*, *953*, 012215. doi: 10.1088/1742-6596/953/1/012215

Puretec. (2023). *What is Reverse Osmosis?* Retrieved from https://puretecwater.com/reverse-osmosis/what-is-reverse-osmosis

Qu, S. Q., & Dumay, J. (2011, 8). The qualitative research interview. *Qualitative Research in Accounting & Management*, *8*(3), 238–264. doi: 10.1108/11766091111162070

Richards, C. E., Lupton, R. C., & Allwood, J. M. (2021, 2). Re-framing the threat of global warming: an empirical causal loop diagram of climate change, food insecurity and societal collapse. *Climatic Change*, *164*(3-4). doi: 10.1007/s10584-021-02957-w

Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S. E., Donges, J. F., ... Rockström, J. (2023, 9). Earth beyond six of nine planetary boundaries. *Science Advances*, *9*(37). doi: 10.1126/sciadv.adh2458

Rinaldi, S. (2004). Modeling and simulating critical infrastructures and their interdependencies. In *37th annual hawaii international conference on system sciences, 2004. proceedings of the* (p. 8 pp.). IEEE. doi: 10.1109/HICSS.2004.1265180

Rinaldi, S., Peerenboom, J. P., & Kelly, T. K. (2001). Identifying, Understanding, and Analyzing. *IEEE Control Systems Magazine*, 11–25.

Rockström, J., Steffen, W., Noone, K., Persson, A., Chapin, F. S., Lambin, E., ... Foley, J. (2009). Exploring the Safe Operating Space for Humanity. *Ecology and Society*, *14*(2). Retrieved from http://www.jstor.org/stable/26268316

Santella, N., Steinberg, L. J., & Parks, K. (2009, 7). Decision Making for Extreme Events: Modeling Critical Infrastructure Interdependencies to Aid Mitigation and Response Planning. *Review of Policy Research*, *26*(4), 409–422. doi: 10.1111/j.1541-1338.2009.00392.x

Schotten, R., Mühlhofer, E., Chatzistefanou, G. A., Bachmann, D., Chen, A. S., & Koks, E. E. (2024, 3). Data for critical infrastructure network modelling of natural hazard impacts: Needs and influence on model characteristics. *Resilient Cities and Structures*, *3*(1), 55–65. doi: 10.1016/J.RCNS.2024.01.002

Schwartz, G. M., & Nichols, J. J. (2006). *After Collapse: The Regeneration of Complex Societies.* University of Arizona Press. Retrieved from http://www.jstor.org/stable/j.ctt181hxqb

Sehlke, G., & Jacobson, J. (2005, 9). System Dynamics Modeling of Transboundary Systems: The Bear River Basin Model. *Groundwater*, *43*(5), 722–730. doi: 10.1111/j.1745-6584.2005.00065.x

Setola, R., & De Porcellinis, S. (2008). A Methodology to Estimate Input-Output Inoperability Model Parameters. In (pp. 149–160). doi: 10.1007/978-3-540-89173-4

Setola, R., & Theocharidou, M. (2016). Modelling Dependencies Between Critical Infrastructures. In (pp. 19–41). doi: 10.1007/978-3-319-51043-9

Stofberg, S., Pronk, G., van Huijgevoort, M., Raat, K., & Bartholomeus, R. (2023, 5). *Werken aan waterbeschikbaarheid: inzichten en uitdagingen.* Retrieved from https://www.h2owaternetwerk.nl/vakartikelen/werken-aan-waterbeschikbaarheid-inzichten-en-uitdagingen

Tainter, J. (1988). *The Collapse of Complex Societies.* Cambridge: Cambridge University Press.

Tainter, J. (2022, 6). *How did climate influence the collapse of ancient civilizations? - Explaining Collapse.* Webinar Tipping Elements.

Taleb, N. N. (2007). *The Black Swan: The Impact of the Highly Improbable.* New York City: The Random House publishing group.

Tangena, B. H. (2014). *Behoeftedekking Nederlandse drinkwatervoorziening 2015-2040* (Tech. Rep.). RIVM. Retrieved from www.rivm.nl

Tierney, K., & Bruneau, M. (2007, 2). Conceptualizing and measuring resilience: A key to disaster loss reduction. *TR News*, *250*, 14–17.

URS. (2010, 1). *Adapting Energy, Transport and Water Infrastructure to the Long-term Impacts of Climate Change* (Tech. Rep.). Retrieved from http://www.opsi.gov.uk/acts/acts2008/ukpga_20080027_en_1].

van Leerdam, R., Rook, J., Riemer, L., & van der Aa, N. (2023). *Waterbeschikbaarheid voor de bereiding van drinkwater tot 2030 - knelpunten en oplossingsrichtingen* (Tech. Rep.). RIVM.

van Thienen, P., Chatzistefanou, G. A., Makropoulos, C., & Vamvakeridou-Lyroudia, L. (2023, 12). What water supply system research is needed in the face of a conceivable societal collapse? *Journal of Water and Climate Change*, *14*(12), 4635–4641. doi: 10.2166/wcc.2023.351

Ventana Systems. (2024). *Vensim Professional.* Retrieved from https://vensim.com/vensim-brochure/

Vonk, E., Cirkel, G., & Leunk, I. (2017, 11). *De gevolgen van klimaatverandering en vakantiespreiding voor de drinkwatervraag* (Tech. Rep.). KWR.

Weiss, H., & Bradley, R. S. (2001, 1). What Drives Societal Collapse? *Science*, *291*(5504), 609–610. doi: 10.1126/science.1058775

Wuijts, S., van der Grinten, E., Meijers, E., Bak-Eijsberg, C., & Zwolsman, J. (2013). *Impact klimaat op oppervlaktewater als bron voor drinkwater: van knelpunten naar maatregelen* (Tech. Rep.). RIVM. Retrieved from www.rivm.nl

Xu, C.-Y., Seibert, J., & Halldin, S. (1996, 5). Regional water balance modelling in the NOPEX area: development and application of monthly water balance models. *Journal of Hydrology*, *180*(1-4), 211–236. doi: 10.1016/0022-1694(95)02888-9

Yasa ET. (2022, 10). *Reverse Osmosis Reject and Brine Treatment for Desalination Plants.* Retrieved from https://www.yasa.ltd/post/reverse-osmosis-reject-and-brine-treatment-for-desalination-plants-zero-liquid-discharge-solutions

Zimmerman, R. (2009). *Understanding the Implications of Critical Infrastructure Interdependencies for Water* (Tech. Rep.). Retrieved from http://research.create.usc.edu/published_papers/7

Zio, E., & Sansavini, G. (2011, 3). Modeling Interdependent Network Systems for Identifying Cascade-Safe Operating Margins. *IEEE Transactions on Reliability*, *60*(1), 94–101. doi: 10.1109/TR.2010.2104211

Appendix A: Interviews

Interview format

Goal of interviews

The interviews will be conducted with the goal of gaining an understanding of the interdependencies in the water sector. The interviewees could be asked to describe their mental model of the interdependencies and rate each dependency according to its importance to the water sector. The interviewees will also be asked about their knowledge of what they know about the sector, or whether it is a black box to them. The interviewees could also be asked to recall an example where disruptions happened that affected their daily operations, in order to allow them to mention how the water sector responds to disruptions.

The interview output information will be used to answer the following subquestions:

- What are the sectors that the water sector is dependent on, forming the water sector's web of dependencies?
- How can the water system and its interdependencies with other sectors be represented effectively?
- How can the dynamics within and across the interdependent sectors be determined and represented?

Interview questions

The interviewer introduces themselves and the topic, as well as the goal of this interview.

Part 1: Profile

1. What is your background and current role?
   (a) If you were to place yourself at the following three levels, which would you be: strategic level, management level, operational level?
2. For how many years have you been working in the water sector?

Part 2: Dependencies

Interviewer introduces an example of sector/component dependencies: Imagine the health sector, they are dependent on the water sector for a supply of clean drinking water, the chemical sector for a supply of disinfection material, the pharmaceutical industry for medicine, certain manufacturing industries for hospital equipment, etc.

3. How do you imagine this may apply to the water sector? Could you name some examples of such sectors?
   (a) (In case one is mentioned that is particularly interesting) could you expand on that?
4. Do you think you have a good overview of the dependencies of the water sector?
   (a) If yes: how do you keep track of these?
   (b) If no: How would you try to get a better insight?

Interviewer shows the image of the web of dependencies that include the sectors being considered. The following questions are asked about each link from a sector to the water sector, e.g. energy sector to water sector only.

5. What are the most important components that are being provided to the water sector by this specific sector?
6. How would you rate the level of dependency on this sector out of 5?

After having discussed each link individually the following questions are asked:

7. Do you agree with the selection of these sectors or are there more sectors that come to mind which might be more relevant?
8. Are you mostly aware about where these components come from or are produces, or are you only interested in that they are actually delivered? (In case this question is confusing, name the example of knowing where chemicals are produced before they are delivered).

Part 3: Resilience of the water sector

Interviewer gives a description of resilience of the water sector.

9. What specific measures do you have in place that allows the water sector to be resilient with regards to these dependencies?

Part 4: Own experience/example

10. Could you give an example of a rapid or slow onset disruption from one or more sectors because of which the water sector experienced problems? Name the cause, which sectors, what effect and how this was solved or dealt with.

Part 5: Closing

11. What knowledge gaps have you noticed in your work, or my work?
12. If you have any further questions, tips, or sources to share, please let me know.

Appendix B: Model Input

Model parameters

Name	Parameters	Parameter name	Type	Range
Population growth	3	population_change	Integer	-500 to 500
		population_k	Real	0.25 to 0.75
		population_x	Real	10 to 20
Infrastructure damage curve	3	damage_k	Real	3 to 5
		damage_lambda	Real	50 to 20
		damage_t	Real	0.2 to 0.5
Electricity damage curve	3	electricity_k	Real	1.25 to 2
		electricity_lambda	Real	50 to 5
		electricity_t	Real	0.5 to 0.8
Telecom damage curve	3	telecom_k	Real	1.25 to 2
		telecom_lambda	Real	50 to 5
		telecom_t	Real	0.5 to 0.8
Financial and banking damage curve	3	financial and banking_k	Real	2 to 3
		financial and banking_lambda	Real	20 to 10
		financial and banking_t	Real	0.2 to 0.8
Fuel damage curve	3	fuel_k	Real	1.25 to 2
		fuel_lambda	Real	50 to 20
		fuel_t	Real	0.2 to 0.5
Chemical damage curve	3	chemical_k	Real	1.25 to 2
		chemical_lambda	Real	50 to 20
		chemical_t	Real	0.2 to 0.5
Manufacturing damage curve	3	manufacturing_k	Real	1.25 to 2
		manufacturing_lambda	Real	50 to 20
		manufacturing_t	Real	0.2 to 0.5
Transportation damage curve	3	transportation_k	Real	3 to 5
		transportation_lambda	Real	50 to 20
		transportation_t	Real	0.2 to 0.5
Contamination damage curve	3	contamination_k	Real	3 to 5
		contamination_lambda	Real	50 to 20
		contamination_t	Real	0.2 to 0.8

Table B.1: Uncertainties in model

Input Output analysis

Labeled sector	**Included sectors**
Manufacturing	Machine-industrie
Transportation	Vervoer over land
	Vervoer over water
	Vervoer door de lucht
Chemical	Chemische industrie
People	Lonen
Consumers	Consumptieve bestedingen door huishoudens
	Consumptieve bestedingen IZW huishoudens
Electricity	Energiebedrijven
Fuel	Aardolie-industrie
Telecom	Telecommunicatie
IT infrastructure	IT-dienstverlening
	Diensten op het gebied van informatie
Finance and banking	Bankwezen
	Overige financiële dienstverlening
Water	Waterleidingbedrijven

Table B.2: Division of subcategories in input output analysis

Expert dependency matrix

Table B.3: Informed dependency matrix

Component i	**Component** j	**Score**	**Comments**
Specialized workers	Specialized workers	8	Specialized workers rely on teamwork and the expertise of colleagues to address issues effectively, representing a medium to high dependence.
	Telecommunications	8	Effective collaboration requires constant contact, facilitated by telecommunications. In emergencies, portable radios are used as a backup, dependent on a robust telecommunications network.
	Transportation	5	Accessibility to work locations is essential, requiring available transportation methods. While alternatives like bicycles could still be available, they still depend on maintained road networks.
Population	Electricity	10	Electricity is critical for operating tools, devices, and infrastructure, as well as for home appliances and comfort.
	Telecommunications	8	Telecommunications is key to maintaining social relations, accessing information, and ensuring emergency services, with its absence causing possible isolation and panic.

Table B.3 – continued from previous page

Component i	**Component** j	**Score**	**Comments**
	Financial and banking	6	Financial services are fundamental to daily life, with bank failures potentially eroding public confidence and inciting panic, though effects may be more short-lived.
	Transportation	4	Limited transportation options can reduce mobility, with the public less able to travel.
Electricity	Specialized workers	7	Technical experts are vital for maintaining, diagnosing, and repairing the power grid.
	Electricity	7	Disruptions in the power network can complicate the ability to resolve issues, with electricity needed for grid communication and transformation processes.
	Fuel	8	Fuel is sometimes necessary for electricity generation, particularly when renewable sources can't meet demand.
	Telecommunications	6	Telecommunications is crucial for real-time grid monitoring, maintenance coordination, and emergency response.
	Financial and banking	4	Finance supports maintenance and emergency repairs, with a larger role in network expansion and continuity.
Fuel	Specialized workers	8	Fuel provision relies on specialists for exploration, extraction, refining, and distribution.
	Fuel	4	Production and refining processes may require fuel inputs.
	Telecommunications	7	Telecommunications supports efficient supply chain operation, worker communication, and demand awareness.
	Financial and banking	4	The financial sector is key for investment and supply chain management; less critical in immediate emergencies.
	Transportation	10	Without pipelines, fuel relies on transport by trucks or other carriers.
Telecommunications	Specialized personnel	8	Network efficiency depends on skilled specialists for repair and maintenance.
	Electricity	10	Telecommunications cannot operate without electricity, with backup generators providing limited support.
	Telecommunications	8	Communication services are essential for network issue identification and repair crew coordination.
	Financial and banking	4	Financial resources fund long-term maintenance and expansions, though less critical in immediate emergencies.
Automated processes	Specialized workers	9	Automated systems require specialists with specific knowledge for troubleshooting.

Table B.3 – continued from previous page

Component i	**Component** j	**Score**	**Comments**
	Electricity	10	Full reliance on electricity for operation, including PLCs and SCADA systems.
	Telecommunications	6	Certain systems, like SCADA, depend on telecommunications, while others, like PLCs, do not.
Financial and Banking	Specialized workers	7	Operations rely on specialists for expertise in finance, compliance, and technology.
	Electricity	9	Essential IT infrastructure and banking services require a stable electricity supply.
	Telecommunications	8	Transaction management and client communication depend on telecommunications.
	Financial and banking	10	Interdependent financial services and markets are fundamental for economic growth.
OpEx	Financial and banking	8	Operating expenses are influenced by financial availability for immediate use.
CapEx	Financial and banking	4	While affected by current financial conditions, CapEx relies more on operating performance.
	OpEx	10	Capital expenditures are directly determined by the performance of operating expenses.
Chemical	Specialized workers	8	Specialized workers are needed for the chemical industry, from exploration to distribution.
	Electricity	6	Production of chemicals may depend on electricity.
	Telecommunications	7	Efficient supply chain management in the chemical industry requires telecommunications.
	Financial and banking	4	Financial resources are important for investment and logistics; less critical in immediate emergencies.
	Chemical	8	Self-reliant chemical production can be disrupted by supply chain issues.
	Transportation	10	Chemicals rely on transportation for delivery to clients, lacking dedicated pipelines.
Manufacturing	Specialized workers	6	Specialized workers are essential in manufacturing equipment for the water sector.
	Electricity	8	Electricity is vital for running manufacturing facilities and producing materials.
	Telecommunications	7	Telecommunications support automated manufacturing systems and are key for supply chain management.

Table B.3 – continued from previous page

Component i	**Component** j	**Score**	**Comments**
	Financial and banking	4	Investments and supply chain management depend on finances, which are less important in emergencies.
	Manufacturing	8	Disruptions in own production can halt operations, especially as supply chains are interlinked among various manufacturers.
	Transportation	9	The manufacturing sector relies on transportation networks to deliver and receive components.
Transportation	Specialized workers	6	Skilled drivers are necessary for operating vehicles and ensuring the effective transport of goods, applicable to specific transport modes.
	Electricity	6	Electricity powers certain transport modes, but the sector predominantly relies on fuel.
	Fuel	9	The high reliance on fuel for transportation underlines its critical role in the sector.
	Telecommunications	8	Telecommunications are imperative for the coordination of transport operations and network maintenance.
	Financial and banking	4	Finance impacts the transport sector's supply chain and investment capabilities, with reduced importance during immediate crises.
	Transportation	10	The sector is extremely susceptible to disruptions within its own networks, affecting the entire transportation infrastructure.

Appendix C: Model Analysis

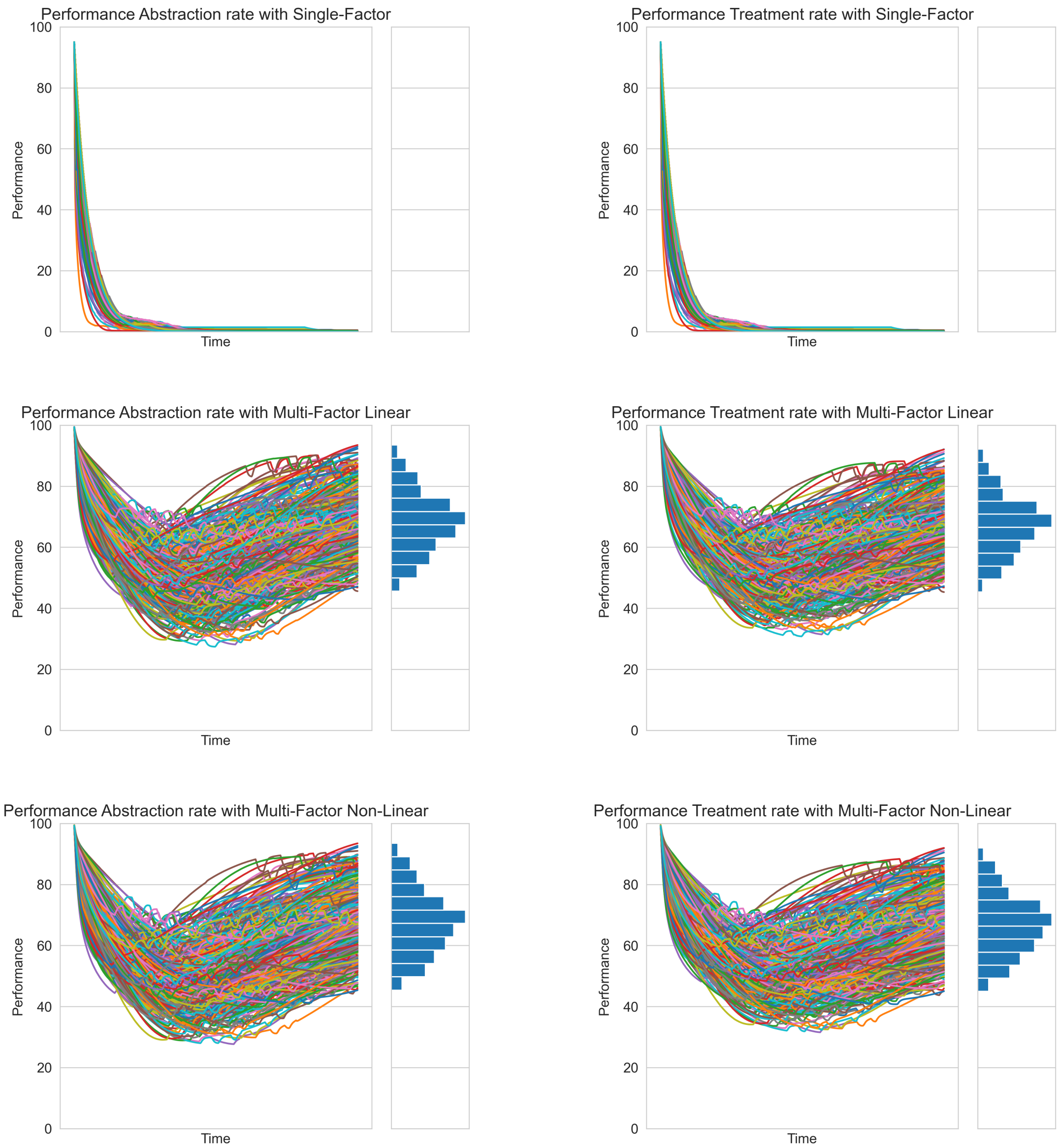


Figure C.1: Time series outcomes exp 2: IO matrix

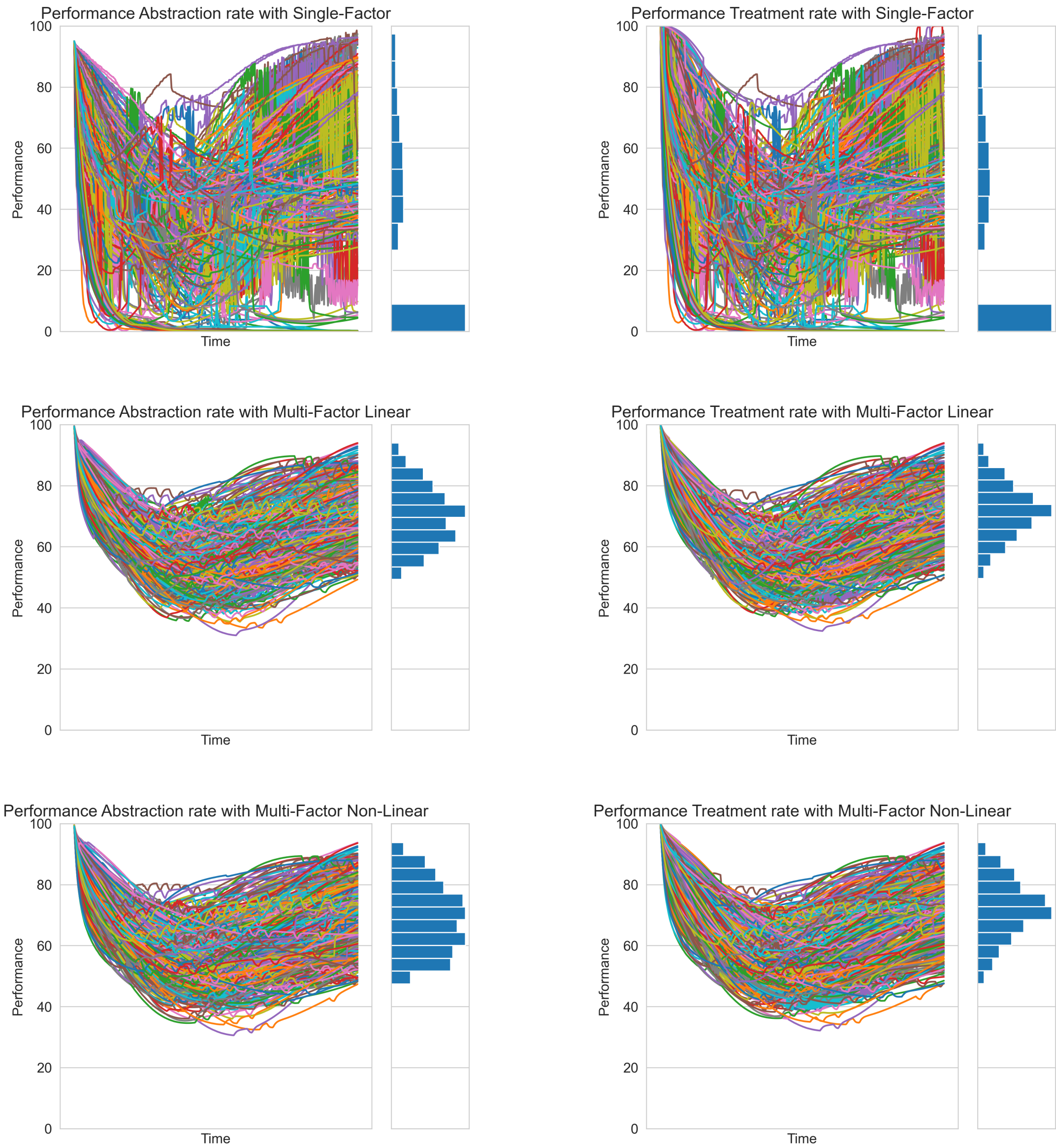


Figure C.2: Time series outcomes exp 3: adaptation