Pragmatic Constructions

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Pragmatic Constructions

Simulation and the Vulnerability of Technological Cultures

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“Beneath the fabricating and universal writing of technology, opaque and stubborn places remain. The revolutions of history, economic mutations, demographic mixtures lie in layers within it, and remain there, hidden in customs, rites, and spatial practices. The legible discourses that formerly articulated them have disappeared, or left only fragments in language. This place, on its surface, seems to be a collage. In reality, in its depth it is ubiquitous. A piling up of heterogeneous places. Each one, like a deteriorating page of a book, refers to a different mode of territorial unity, of socioeconomic distribution, of political conflicts and of identifying symbolism.” (de Certeau 1988, 201)

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Acknowledgments

I write these words on a sunny day in Utrecht, the city where I lived when I applied for the job that allowed me to produce the book that you are now reading. I cannot help but think what a remarkable, inspiring, beautiful (though at times frustrating), and somehow long-yet-short or short-yet-long process the writing of this book has been. It has been a true privilege throughout and I could not have done it without so many wonderful people to guide me along the way.

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Map of The Netherlands

Figure 1.1 Map of The Netherlands. © Michael Schmeling

Afsluitdijk	1	Lek	9	Scheveningen	17
Biesbosch	2	Lelystad	10	Tilburg	18
Delft	3	Maas	11	Volkerak Zoommeer	19
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1. Introduction: the vulnerability of technological cultures

1.1 The Netherlands as a vulnerable technological culture

Among the many images that the Netherlands will be able to conjure up, water will certainly feature prominently. The history of the Netherlands is replete with adversity and catastrophe. Sedimentation and salinization of bodies of water often meant economic hardship for areas previously considered to be prosperous loci for trade. Floods have occurred throughout the ages, such as the First and Second St. Elisabeth's floods in 1404 and 1421, the St. Felix Flood in 1530, the infamous 1953 Flood of large parts of the *Zeeland*[1] province, and the 1993 and 1995 flooding of large areas in the south of the Netherlands. Especially the Flood of *Zeeland* has become firmly anchored in Dutch culture.

The geographical position of the Netherlands does not only imply disaster but also economic prosperity, though the Dutch face a continuing struggle to maintain their habitat. This ambivalent relationship with water is underscored by accounts of the history of the Netherlands, which often describe zealous Dutch who over time improved their ability to construct dikes and reclaim land. In the North of the Netherlands, elevated patches of land known as *terpen* and *wierden* were constructed as early as the 5th century B.C. to provide protection against floods. The Roman historian Pliny the Elder speaks of a "miserable race" (Pliny 1960, 387), "resembling sailors in ships when the water covers the surrounding land, but shipwrecked people when the tide has retired." (Pliny 1960, 389)[2] The construction of dikes from the 12th century onward improved living conditions for many. This was followed by the reclamation of various lakes in the West of the Netherlands by means of windmills in the 17th century. From the 18th century, the use of steam engines enabled the reclamation of even larger bodies of water, such as the *Haarlemmermeer*. During the 20th century, the *Zuiderzee* was shut off from the North Sea by means of the *Afsluitdijk*, and henceforth became known as the *IJsselmeer* (see section 3.1). The 1953 flooding of *Zeeland* led to the construction of the pride of the stable of hydraulic engineering in the Netherlands: the world-famous *Deltawerken* or Delta Works. Gradually, the many dikes, sluices, dams, storm surge barriers, and drainage systems

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[1] Throughout the book, I will refer to geographical locations in the Netherlands that may be unfamiliar to the reader. Please refer to the map of the Netherlands on page 13.

[2] Pliny's description is not exactly flattering: "And these are the races that if they are nowadays vanquished by the Roman nation say that they are reduced to slavery! That is indeed the case: fortune oft spares men as a punishment." (Pliny 1960, 389)

established a vast hydraulic system, which is of crucial importance for the safety, habitability, and economy of the Netherlands. It should come as no surprise that the Netherlands is often portrayed as being 'man-made'.[3]

For many years, guaranteeing safety by all means necessary was a guiding principle in water management in the Netherlands. However, the interventions enabled by engineering in some cases had a detrimental effect on the Dutch landscape and its ecosystems. Eventually, various parties who emphasized ecological sustainability gained foothold in the political arena from the 1970s and 1980s (Disco 2002; Lintsen 2002, 566ff.; van der Vleuten & Disco 2004, 302ff.). Today, Dutch water management no longer operates exclusively in terms of keeping the water out at all costs, but increasingly takes the form of 'adaptive' water management and flood protection, which entails an approach to water-related risks that balances interests related to safety, ecology, and spatial planning. This wider repertoire of actions also includes monitoring and evacuation, and emphasizes adaptability rather than resisting water (de Vriend 2009).

Despite admirable interventions of the Dutch throughout the centuries, water-related threats have far from subsided, and ensure that the Netherlands remain at risk or vulnerable to floods, failing dikes, dams, and sluices, and ecological adversities. Today, a large part of the Dutch population and economic activities takes place in the west and southwest of the Netherlands – a highly urbanized delta where the impact of floods is likely to be severe, though estimates of the potential damages vary. According to the Central Bureau for Statistics (*Centraal Bureau voor de Statistiek*) about 3.4 million inhabitants or 21% of the total population live below sea level (Centraal Bureau voor de Statistiek 2008, 65). 19% of the GNP is earned below sea level, although a total 32% of the GNP is earned in areas that are considered prone to flooding. (Centraal Bureau voor de Statistiek 2008, 64) The Transport and Water Management Inspectorate (2006) makes a more alarming assessment, and claim about nine million inhabitants of the Netherlands live in areas prone to flooding that produce two thirds of the GNP. (Transport and Water Management Inspectorate 2006, 4) Climate change is a present-day challenge that further complicates the relationship between the Netherlands and its surroundings since it can lead to "higher sea levels, larger quantities of precipitation alternating with longer periods of drought, and bigger peaks and lows in the river water supply." (Hooimeijer

[3] For a more elaborate overview of the rich history of water management in the Netherlands, see for example Dirkzwager et al. 1977; Bosch & van der Ham 1998; van de Ven 2004; Hooimeijer 2005; Rooijendijk 2009.

2009, 8) In 2008, the *Deltacommissie* (Delta Committee) published a report (Deltacommissie 2008) that contains a wide-ranging repertoire of recommendations to the Dutch government that need to be implemented before 2100 in order to improve the safety of flood defenses, maintain or improve ecological sustainability, and ensure economic prosperity. Aerts et al. (2008) have calculated that a flooding of all dike-ring areas (land protected from flooding by dikes) in the year 2000 would have amounted to a total of 190 billion euros of damage (Aerts et al. 2008, 14). If the Dutch fail to take proper measures, the effects of rising sea levels are alarming. By the year 2040, a rise in sea levels of 24 to 60 centimeters amounts to potential damages between 400 and 800 billion euros. By the year 2100, a rise of sea levels by 150 centimeters implies potential damages of up to 3.700 billion euros (Ibid.).

Research questions and aim of the book

In this book, I focus on an important technological aspect of water management in the Netherlands: the use of simulations and models to cope with water-related risks. My analysis starts from two premises. First of all, the safety, habitability, and economic and environmental sustainability of the Netherlands are firmly intertwined with the use of simulations and models, which are used to define, monitor, predict, counter, and communicate water-related risks. This 'social reliance' (Pippin 1995, 46) on simulations and models underlines that the Netherlands need to be characterized as a 'technological culture' (Bijker 2006). The latter term "highlights that the modes of inhabitation and signification (culture) that make up our world are technologically mediated." (van Loon 2002, 9) More generally, the technological mediation that van Loon refers to ranges from the production and distribution of goods, services, and cultural products, to the creation and maintenance of systems crucial for human survival (e.g. the hydraulic system of the Netherlands). Present-day societies cannot be conceptualized without reference to the technological means of their functioning. There is no 'culture' outside of technological mediation.[4] However, technologies are not merely mute instruments: their various applications influence the technological cultures that depend on their functioning. For example, technological malfunctioning can have a profound effect on a technological culture, as well as the potentially disruptive and sometimes unforeseen effects of

[4] Numerous authors (e.g. Derrida 1976; Stiegler 1998; Mackenzie 2002; Bradley 2011) have opposed the idea of technology as a supplement, which would imply a self-sufficient existence of human life and societies prior to technologies.

innovations, e.g. nanotechnology and mobile communication. In sum, the use of technologies in technological cultures is Janus-faced, since technologies not only function as instruments used for particular purposes, but also shape technological cultures due to their various applications and effects.

The second premise concerns the mediating role of simulations and models in the Netherlands, seen as a technological culture in the foregoing sense. As I point out in more detail in chapter 2, simulations and models play an inscriptive role in the process of defining, monitoring, predicting, countering, and communicating water-related risks. Although simulations and models will bear varying degrees of semblance to their objects of study (their 'target systems'), they are not straightforward representations of the world 'out there'. The development and use of simulations and models requires that target systems are translated or converted into physical or computational models by means of which experiments can be conducted. As a result, the use of simulations and models may be accompanied by assumptions, uncertainties, and blind spots.

In the light of these inscriptive aspects of simulations and models, simulation practice has a double meaning. Although simulations and models fulfill a crucial and instrumental role in defining, monitoring, predicting, countering and communicating risks (identified as social reliance in the foregoing), their use can also render technological cultures vulnerable by making them susceptible to risks. The main title of this book, 'Pragmatic Constructions' is derived from a publication edited by Lenhard et al. (2006): 'Simulation: Pragmatic Constructions of Reality'. As Küppers et al. explain in their introductory chapter in the aforementioned edited book: "[t]he term Pragmatic Constructions of Reality […] alludes to the affinities of simulation to hyperrealistic models and experiences that do not only represent the world but also create a new one: A virtual world." (2006, 21) In addition,

> "[c]omputer simulations can *imitate* the dynamics of a complex *process* or complex *function* by employing generative mechanisms. These mechanisms are constructed in pragmatic ways and may employ sophisticated visualizing and experimental strategies. At first sight and on some levels, simulation even seems to overcome the […] ontological split between 'reality' and 'representation' with the aid of its simulation-generated, visually overwhelming images […] But can they dissipate the fundamental tension between reality and its perfect imitations?" (Ibid., original emphasis)

Like Küppers et al., I study whether and how simulations and models carry the relationship between reality and its imitations to the extreme by acting as 'stand-ins' for target systems, and also ask whether technological cultures are put at risk when this occurs. I hasten to add that I do not persuade the reader to adopt a dismissive view of simulations and models. Rather, I aim to show how simulations and models are used in the context of risk assessment, whilst paying close attention to their inscriptive effects.

In the light of these two premises (the social reliance claim and the inscriptive role of simulations and models), the guiding questions of this book then are the following: *how are simulations and models used in technological cultures to cope with risks, and how may social reliance on simulations and models put technological cultures at risk?* By answering these questions, this book assesses the impact of social reliance on simulations and models. Although the empirical domain of this book is limited to water management in the Netherlands, domains outside of water management (e.g. climate science, logistics, nanotechnology) rely more and more on simulations and models, which can increase the scope and relevance of my findings. The success of water management in the Netherlands is known throughout the world, and often serves as a textbook example of state of the art engineering. Although I do not wish to debunk that image, I do think vulnerabilities can be pointed out despite the many achievements of those involved with water management in the Netherlands. As such, my study of simulation practice in Dutch water management can provoke critical studies of the successes of engineering. In the remainder of this first chapter, I show how my book relates to studies of risk, vulnerability, and resilience in technological cultures. In addition, I discuss the methodology used to address the research questions and introduce the empirical domain that is the subject of this book.

1.2 Risk, vulnerability, and resilience in technological cultures

The vulnerability of the Netherlands to water-related risks is not merely an intrinsic property related to its geographical position. According to recent studies of risk and vulnerability informed by social constructivism (e.g. Summerton & Berner 2003; Bijker 2006; Hommels et al. forthcoming), vulnerability should be studied by taking into account the temporal, spatial, and cultural contexts specific to particular individuals, organizations, or systems. The aforementioned social reliance on simulations and models implies that these technologies are deeply intertwined with present-day technological cultures and constitute a 'technocultural milieu' (Menser & Aronowitz 1996, 24). This observation need not be tantamount to the idea that societal developments are determined by autonomously developing technologies – a conceptualization of technology known as 'technological determinism' (Bimber 1994; Heilbroner 1994; Wyatt 2008). Social constructivist studies of technology (Pinch & Bijker 1984; Bijker et al. 1987; MacKenzie & Wajcman 1999) problematize technological determinism, since neither the technical nor the social are determinant exclusively. In other words, technological cultures do not consist of "elements that are a priori and intrinsically social, technical, economic, or cultural." (Bijker 1995b, 249) Rather, all of these elements exert some effect within 'sociotechnical ensembles', which form a "seamless web". (Ibid.)[5]

Constructivist views of technological cultures can help "to make explicit the political dimensions of the role of science and technology, to question the self-evident character of technological culture, and to put science and technology on the public agenda for political deliberation." (Bijker 2001, 21) Studies of technological cultures can unravel the tightly woven 'seamless webs' of sociotechnical ensembles, and thereby articulate the relationships between risk, technology, and culture. This book can be aligned with such efforts, since it aims to show how vulnerability and techno-scientific practices that feature prominent use of simulations and models are intertwined, and thus cannot be reduced to self-contained aspects of technological cultures. The title of this book refers to the plural 'technological culture*s*' to emphasize the idea that different relationships between vulnerability, technology, and culture also constitute different technological cultures. There is no single technological culture, but rather different technological cultures that align themselves with the threats that put them at risk in different ways. For example, the Netherlands and the USA have a different approach to water: whereas the former technological culture is (still) largely concerned with keeping the water out, the latter technological culture is more devoted to mitigation in order to minimize damage and the amount of casualties in case things do go wrong (Bijker 2007a; Bouwer & Vellinga 2007; Kuster 2008). An assessment of the role of simulations and

[5] For the reader unfamiliar with constructivist studies of technology and the critique of technological determinism in Science and Technology Studies (STS), the case studies in chapters 3 to 5 will provide ample evidence of why the technical and the social cannot be neatly distinguished. Commitments to technological determinism will feature most prominently in chapter 3, where I show that technological innovations have had an important effect on simulation practice, but are not the sole explanatory component of that effect. Hence, technology needs to be interpreted as a component of a socio-technical constellation that consists of both technological artifacts and cultural, economic, social, and political elements. Such a "soft determinism is vague and is not really determinism at all, as it returns us to the stuff of history, albeit a history in which technology is taken seriously." (Wyatt 2008, 173)

models in technological cultures will help to think of different ways in which these technologies can be used, and how different forms of simulations practice contribute to differences between technological cultures. In this section, I engage existing literature on risk, vulnerability, and resilience in order to flesh out a rigorous approach to modeling practices. In addition, I use this discussion to point out how and why my analysis of modeling practices emphasizes vulnerability rather than risk.

Risk

Many disciplines, such as the natural sciences, engineering, psychology, and economics take a quantitative approach to risk. Such 'technoscientific approaches' (Wyatt & Henwood 2006, 233) start from the assumption that risks can be measured and weighed objectively by means of quantitative methods, which are used to calculate the likelihood of exposure to risks and the subsequent impact of the occurrence of those risks. Such risk assessments are often based on a "deficit model of lay people's understanding" (Ibid.), which dictates that "people should be given more information from experts and if this is then correctly interpreted, irrational fears will disappear and lay views or 'perceptions' will come to resemble more closely the objective understandings of experts (the 'real' risks)." (Ibid.) In other words, technoscientific approaches are geared towards expert assessments of risks, and value the latter as the only approach to risk that is systematic, thorough, and objective.

Yet producing such scientific assessments of risks can be a rather problematic endeavor, since many risks turn out to be less tractable than commonly acknowledged. The two main aspects of technoscientific risk calculations – the likelihood of a problem occurring and the consequences of its occurrence – often defy exact or exhaustive specification. In some cases, neither the likelihood nor the consequences of risks are understood fully or known at all, a problem commonly identified as 'uncertainty'. Gross defines uncertainty as "a situation in which, given current knowledge, there are multiple possible future outcomes." (Gross 2010, 3) In this sense, the desire to quantify risks may not only increase awareness of risks, but also contribute to awareness of the uncertainties concomitant with risk assessments. Gross is convinced that increases in knowledge can also lead to awareness of the limits of knowledge in a particular area, a state he defines as ignorance (see also Stirling 2007 and 2008).[6] In such cases, quantitative approaches to

[6] As I will show in chapter 4, uncertainty harbors a variety of challenges to risk assessments, such as 'ignorance', which Gross defines as "knowledge about the limits of knowing in a certain area" that

risk may exacerbate rather than diminish the concern about risks. Furthermore, it is doubtful that all risks can be converted into the same quantitative parlance, since different disciplines use diverging ways to calculate risks (Stirling & Mayer 1999, quoted in Yearley 2005, 132). Risks may be communicated through numbers and percentages, but different risks (e.g. medical, infrastructural, and industrial risks) may feature different conventions to predict the likelihood of risks and calculate the effects of their occurrence (Yearley 2005, 132). What is more, the risks at play in different fields may feature different kinds of damage and compensation. In sum, it is questionable whether these different forms of risk can be brought into the same calculus, nor whether they should be, since doing so will tend to downplay the contingency of the quantitative methods through which risk assessments are established.

Approaches to risk in the social sciences have problematized the quantitative orientation of the aforementioned technoscientific risk assessments, and propose alternative ways of addressing risk that are often based on a constructivist framework (e.g. Feldman 2004). Wyatt and Henwood (2006, 233) quote the work of Lupton (1999), who distinguishes three major currents in studies of risk in the social sciences: first, work on the so-called 'risk society', first introduced by Beck and Giddens. Second, Douglas' cultural and symbolic interpretations of risk. Third, the governmentality approach, which draws its inspiration from the work of Foucault.

In the social sciences, the publication of the work of Beck (1986) and Giddens (1990 and 1991) heralded a broader turn towards risk and reflexivity (Wyatt & Henwood 2006, 233). Reflexivity concerns the way in which social actors "actively monitor their actions and contexts, drawing upon the knowledge available to them." (Ibid.) Both Beck and Giddens consider risk as a phenomenon characteristic of modernity. Beck distinguishes 'hazards' or 'dangers' that could be found in pre-industrial or traditional cultures, from the 'risks' that characterize present-day industrial societies. Beck does not wish to argue that today's societies are more hazardous than the pre-modern world, but that a notion of 'risk' could not be found in traditional cultures. Hazards or dangers were considered as pre-given, their origin lying in some 'other', e.g. gods, nature, or demons. Risks on the other hand need to be understood as features internal to risk societies. Similarly, Giddens distinguishes between 'hazards' and 'dangers' from what he calls

"increases with every state of new knowledge." (2010, 68) Uncertainty also entails 'indeterminacy', the problem of open-endedness, which applies especially to systems with an organizational or human component (see Wynne 1992). Section 6.3 will further explore Gross' work on ignorance, and will elaborate on indeterminacy.

'manufactured risks', such as taking drugs or driving a car, which are features of modern societies (Wyatt & Henwood 2006, 234).

Importantly, Beck opposes theories that conflate industrialization and modernization, since they fail to understand how risks challenge the existence of present-day societies and lead to institutional and organizational renewal. According to Beck, risk societies arise "through the automatic operation of autonomous modernization processes which are blind and deaf to consequences and dangers […] these produce hazards which call into question – indeed abolish – the basis of industrial society." (Beck 1996, 28 quoted in Elliott 2002, 297) It is in this context of the consequences of the risk society that Beck speaks of reflexivity – the active monitoring of self and context described above. According to Beck, today's societies are lodged between industrial society and advanced modernity, or between simple modernization and reflexive modernization. The latter term signifies a process of reflexivity "that propels men and women into 'self-confrontation' with the consequences of risk that cannot be adequately addressed, at least according to the standards of industrial society." (Elliott 2002, 297) Reflexive modernization refers to a process whereby modernity is confronted with itself, leading to the realization that its earlier incarnations are running out of steam in the face of present-day challenges characteristic of the risk society. These challenges have also led to efforts to regulate the various risks and other 'bads' that are relevant in the risk society, in which science and technology play a crucial and ambivalent role: they form the cause, diagnosis, and (if possible) the means to counter risks.

Beck's thesis of the risk society weds the process of modernization with the development of a calculus of risk. The process of industrialization that characterizes modernity, Beck argues, is accompanied by "societal intervention – in the form of decision-making – that transforms incalculable hazards into calculable risks." (Ibid. p. 295) Risk societies have spawned various kinds of insurance and legal measures in order to equip themselves against the myriad forms of risk that permeate them. Giddens' work on risk shows how risk societies are 'anticipatory' as a result of the ubiquity of risk: "[r]isk concerns future happenings – as related to present practices – and the colonizing of the future therefore opens up new settings of risk, some of which are institutionally organized." (Giddens 1991, 117) However, both Beck and Giddens acknowledge that the certainty of knowledge about risks erodes, and faces continuous contestation in the risk society. Beck claims globalization fractures the calculability of risk once and for all, since many of the risks present-day societies face are not fully understood and therefore cannot be met by accurate calculations. Indeed, present-day risks also feature a degree of universality since far-away accidents may have immediate effects, think for example of the eruption of the Eyjafjallajökull, the Icelandic volcano whose volcanic ashes disrupted international air traffic in 2010.[7] The fact that Beck's book was published in the same year as the meltdown of the Chernobyl nuclear reactor certainly contributed to the enthusiasm of its reception. According to Beck, risk societies have displaced "uncontrollable risks in the natural world" with "risky technologies whose safety crucially depends on how well they are designed, operated and run." (Yearley 2005, 130) It is in this sense that modernization can lead to enhanced security (e.g. increased ubiquity of shelter, food, and health care in comparison to pre-modern societies) but also to novel hazards (e.g. chemical hazards and malfunctioning critical infrastructures).

The second major current in studies of risk in the social sciences is based on the work of Douglas (e.g. Douglas 1992), who also identifies risk as a way to deal with dangers particular to Western societies. Starting from her work in anthropology, Douglas criticizes "cognitive and technoscientific approaches", since "they overemphasize individual perceptions and ignore wider social and cultural contexts in which risk is assessed." (Wyatt & Henwood 2006, 234) Just as sin and taboo offered societies with the ability to blame dangerous individuals who posed threats to the community, scientific and supposedly neutral approaches to risk form important political instruments to earmark certain dangers as 'risks'. For Douglas, omitting cultural aspects from one's analysis of risk leads to a failure to understand risk as an inherently moral classification: risk perceptions and decision making related to risk are always influenced by shared expectations and conventions. There is no neutral assessment of risks, nor is there a single and unambiguous answer to what the repercussions of a hazardous event will be. Instead, Douglas frames risk as a political, moral, and aesthetic evaluation located at least

[7] In my opinion, even the eruption of the Eyjafjallajökull should not be seen as a purely 'natural' disaster. The decision of various European governments to close the airspace above their nations was made on the basis of a predicted risk that featured uncertainties. Volcanic ash typically contains silica glass shards that can melt inside aircraft engines and cause them to fail. However, the risk of engine failure with regard to the distribution and concentration of volcanic ash is not understood thoroughly (yet). Various airlines conducted test flights shortly after the eruption of the Eyjafjallajökull, and found that their aircraft could fly without difficulties. In addition, similar eruptions occur frequently around the globe without causing major disruptions to international air traffic. Since it was not feasible to collect a sufficient amount of data about the distribution and concentration of volcanic ashes on various altitudes above Europe on such a short notice, the use of models to predict the distribution and concentration of volcanic ashes became necessary. However, these models are based on incomplete knowledge about the relationship between volcanic ash and engine failure. A question that comes to mind is whether the affected airlines will push for additional research into modeling the distribution and concentration of volcanic ashes. Another possible outcome is that airlines attempt to forge a political solution by propagating more lenient safety policies that will not cause a major disruption in the case of similar volcanic eruptions.

in part in the political domain. Douglas does not deny the reality of dangers, but does stress the importance of studying the ways in which dangers are politicized and moralized, and emphasizes the importance of anthropology in showing different ways to approach risk that are culturally defined, and subsequently developing a political understanding of risk.

The third major approach to risk in the social sciences refers to the work of Foucault on 'governmentality' (e.g. Foucault 1991a and 1991b), and interprets risk as a governmental strategy to monitor and manage populations. Risk technologies, such as "insurance and actuarial tables, epidemiological data, financial information, government files, surveillance and screening techniques, performances measures, and benchmarking" (Althaus 2005, 576), function as the means to regulate both individuals and populations, and "manage them toward stipulated objectives to minimize 'risks'." (Ibid.) Information thus gathered can then be used to "advise, regulate, and discipline individual behavior." (Wyatt & Henwood 2006, 235) Risk assessments are produced and aggregated by means of the aforementioned risk technologies, and are used to regulate individuals and populations. In addition to being disciplined in accordance with the aforementioned stipulated objectives, individuals discipline themselves by adopting social norms that are aimed at directing their behavior, and judge themselves accordingly. Recent work on 'control' (e.g. Deleuze 1992; Galloway 2004) continues Foucault's work on governmentality and disciplinary power, and argues power has become ubiquitous due to its ability to permeate the very fabric and seams of present-day society, e.g. the abundance of security cameras in everyday environments, or the monitoring of user behavior on the Internet.

The three aforementioned approaches to risk from the social sciences appear to problematize the prospect of finding some incontestable and neutral basis for risk assessments. Jasanoff (1990), whose work can also be placed in the tradition of risk studies from a social science perspective, explicitly rules out that such a basis can indeed be found. Althaus proposes to approach risk not so much as a metaphysical entity or objectively existing reality independent of observation, but rather "as an epistemological reality", meaning that "risk comes to exist by virtue of judgments made under conditions of uncertainty." (2005, 569) In this approach risk can be seen as the application of a "form of knowledge to the unknown in an attempt to confront uncertainty and make decisions." (Ibid. p. 580) Since each discipline has its own approach to risks, Althaus argues this leads to different types of risk assessments. Every discipline may add a piece to the puzzle of understanding risks, and it is important to acknowledge the various ways in which these disciplines engage the production of knowledge about risks, how and by what means they do so, and for whom this is important.

Vulnerability

The notion of vulnerability is related to the notion of risk, but indicates a slightly different approach. Vulnerability can be defined as the state of being at risk, and concerns the ability of individuals, technological artifacts, communities or sociotechnical systems to cope with various kinds of internal and external disturbances. In this book, the terms 'at risk' and 'vulnerable' are used interchangeably. Alternatively, the phrases 'put at risk' and 'rendered vulnerable' indicate the very same, i.e. events or processes whereby individuals, technological artifacts, communities, and sociotechnical systems become susceptible to risks. Importantly, an individual, technological artifact, community, or sociotechnical system may be vulnerable or at risk, without a harmful event actually occurring.

For example, as an individual I am exposed to certain risks when I choose to travel by airplane. Vast and intricate infrastructures are designed to make travel by airplane one of the safest forms of transportation currently known. I may also decide to abstain from travel by airplane altogether, thereby avoiding the possibility of dying in a plane crash, though also limiting my range of possible destinations (at the very least in a practical sense). However, if I do decide to travel by airplane this puts me at risk, since technological malfunctioning or otherwise unforeseen circumstances may lead to a plane crash. However, it is rather likely I will be able to travel safely to various destinations due to the safety of air travel. Even if things do go wrong, there is a chance I will survive, e.g. due to the ability of the pilot or ground personnel to cope with the situation at hand. Insert proverbial knock on wood here. An additional example that is more closely related to the topic of this book is the vulnerability of the Netherlands to water-related risks. Various residential, commercial, and industrial areas are at risk of flooding, though this risk may not manifest itself for some time. Even in the case of a rather disadvantageous scenario, vulnerable areas may be able to cope with the risk of flooding: an evacuation may decrease the amount of casualties, a particular area may act as a buffer zone by being flooded temporarily in order to prevent other areas from flooding, or a flood defense that was not expected to provide protection against water turns out to function well after all and saves the day. Studies of vulnerability explicitly emphasize capacities related to coping with risk rather than looking exclusively at events that have a certain probability and dismal aftermath. This is not to say that studies of risk do not or cannot feature the abilities of individuals, technological artifacts, communities, or sociotechnical systems to cope with risks. Rather, studies of vulnerability take these abilities as their starting point.

There are different approaches to vulnerability. For example, so-called 'livelihood studies' approach vulnerability as "the characteristics of a person or group and their situation that influence their capacity to anticipate, cope with, resist and recover from the impact of a natural hazard." (Wisner et. al. 2004, 11) For example, natural hazards, agricultural and medical innovations, and economic misfortune can impinge upon the ability of certain social groups to cope with such matters (e.g. Quartz 2011). According to Gallopín, vulnerability is constituted "by components that include exposure to perturbations or external stresses, sensitivity to perturbation, and the capacity to adapt." (2006, 294) Bijker describes vulnerability as the ability of technological cultures "to anticipate, resist, cope with, and possibly recover from events that could reduce the system's functional integrity." (2006, 57) The vulnerability of systems is "linked to the performance of subsystems, system components, and to routines and working practices", and is approached by Bijker as "a constructivist concept in the sense that it does not describe a context-independent and intrinsic quality of the system." (Ibid. p. 58-9) As indicated above in my description of technological cultures, vulnerability consists of historical, cultural, social, institutional, and economic processes, which also give shape to a system's ability to cope with disasters and to respond to them. Although Bijker does not speak about vulnerability in essentialist terms, he does consider vulnerability as an irremediable characteristic of technological cultures. Studying the aforementioned seamless webs of technological cultures will yield a more detailed understanding of vulnerability:

> "With a focus on vulnerability of technological culture we do not only study the fragile constitution of modern societies, but can also capture the fragility that is constitutive of our technological culture and thus of its core structures and values." (Ibid. p. 65)

Recent work on sociotechnical systems echoes Bijker's ideas pertaining to vulnerability, and offers a way to study the characteristics that put such systems at risk. Perrow's work on 'normal accidents' (1999) argues that sociotechnical systems increasingly feature 'interactive complexity', indicating that they consist of a large amount of interacting components. In addition, sociotechnical systems feature 'tight coupling', meaning that there is a strong dependence between these components: one failing component will lead to a cascade of malfunctioning dependent technologies that are also part of the system in question. According to Perrow, "we have produced designs so complicated that we cannot anticipate all the possible interactions of the inevitable failures." (Ibid. p. 11) In a world that is more and more populated by technologies that feature interactive complexity and tight coupling, normal accidents are bound to happen. Perrow adds this is a way for him to describe the vulnerability of present-day sociotechnical systems, and not a statement of frequency (Ibid. p. 5).

Explanations for disasters with a significant technological component may alternate between human error and technological malfunctioning, depending on the motives of the explaining party (Galison 2000). Constructivist studies of accidents can contribute to the analysis of vulnerabilities underlying accidents. For example, Law's analysis of the Ladbroke Grove train disaster that took place in 1999 (Law 2000) suggests that some level of train drivers to deviate from rigid protocols is necessary in order for the rail system to function safely and reliably, even though this may also put this system at risk and may in the worst case lead to events with a disastrous outcome. Approaches to vulnerability from the perspective of organizational studies and system theory (e.g. Wackers & Kørte 2003; Wackers 2006; Coeckelbergh & Wackers 2006; Owen et al. 2009) differentiate between different aspects or 'resolutions' of sociotechnical systems, and analyze the repercussions that a decision on one level of a system may have on another level. The malfunctioning of technologies can be explained in terms of errors that existed prior to moments of breakdown, which were simply not discovered in time. Such explanations strengthen discourses around the trustworthiness of technologies by reinforcing the belief that the technologies on which technological cultures rely can still be trusted. However, Wackers shows how sources of malfunctioning technologies were due to actions that were considered as perfectly legitimate solutions to pertinent problems at the time they were taken. Disastrous events can be due to decisions explicitly aimed at the correct and optimal function of a given technologies (Wackers 2006, 38). 'Solutions' developed on one level may have strong repercussions on other levels of the system by impacting its ability to cope with perturbations (Ibid.). Note that Wackers' explanation of cascading errors bears semblance to the ideas of Perrow discussed above

– sociotechnical systems feature interactional complexity, and Wackers' idea of cascading errors can be related to Perrow's idea of 'tight coupling'.

The ability to understand and counter vulnerabilities hinges on analyses of increasingly complex sociotechnical systems. Different perspectives and resolutions can benefit such studies of sociotechnical system. Rather than articulating 'errors', studies of technological cultures can use the notion of vulnerability to study the establishment of local frames of reference that can be at the source of disasters. Engineers can contribute to the study of vulnerabilities by estimating the width of the impact in time and space that decisions made on local levels may have. A "holistic approach" (Coeckelbergh & Wackers 2003, 24) is needed to understand why and how "accidents in technological infrastructures are never merely an accident; they are the result of the interaction between a local event and the system as a whole." (Ibid.) In their study of the factors that influence the vulnerability of technological systems and organizations, Wackers and Kørte (2003) stress the importance of studying routines and programs that make up protocols, which they see as forms of codified knowledge that can diminish the ability of systems to recognize and cope with vulnerabilities. According to Wackers and Kørte,

> "[t]here will always be a gap […] between protocol and practice. This protocol-practice gap is not static and fixed, but fluid and changing. We may postulate the existence of a 'regularity gradient' influencing the formation, extent, and direction of the protocol-practice gap." (Ibid. p. 202)

Wackers and Kørte also indicate that sociotechnical systems will usually attempt to reach 'performative closure', which is the maintenance or achievement of core task completion while maintaining functional system integrity.

The aforementioned protocol-practice gap can be the source of a reduced ability of technological systems to maintain functional integrity. Through a detailed analysis of a helicopter accident, Wackers and Kørte show how the technological system of which the helicopter in question was a part 'drifted' (in other words, changed imperceptibly) to a more vulnerable state. Adaptations to protocol underlying these changes seemed to be right at the moment, but led to malfunctioning components and precluded the system to maintain its functional integrity. The notion of 'drift' was first introduced by Snook (2000) in his analysis of an accidental shoot down of two military helicopters filled with United Nations peacekeepers in northern Iraq by two US fighter planes in 1991. Local adaptations and procedures led to a widening gap between safety regulations and practical operations of the military helicopters, fighter jets, and radar aircraft controlling the area in question. The individual actions seemed innocent at the time, but caused error since the various components of this system of aircraft, helicopters, and protocols could no longer collaborate and integrate as previously intended. Drift then refers to the gradual and covert deviations from (organizational) rules that can lead to accidents.

It is common wisdom that hindsight is 20/20[8] – in the case of drift, latent errors only become apparent or subject to analysis and discussion once something has in fact gone wrong. However, adopting a constructivist stance towards vulnerabilities could enable a more elaborate perspective on the complexity of technological systems. Wackers and Kørte suggest that it is of crucial importance for organizations to develop

> "sensitivity for these messy, locally interactive, and adaptive processes that lead to drift […] part of developing such a sensitivity lies in providing images, metaphors and concepts, words, that can be used to describe and express what is often already known intuitively." (Wackers & Kørte 2003, 204)

Along these lines, Coeckelbergh and Wackers (2006) coin the term 'imaginative capacity' to describe the ability of individuals and organizations to assess a situation or confront a problem. Importantly, the responsibility for confronting crises is shared: "it falls not on the individual alone, but also on the organization of which she is a member – the organization that creates the conditions under which she must perform her task." (Ibid. p. 23) Coeckelbergh and Wackers define the creation of conditions under which operations are carried out as 'design'. By enhancing the system's reflexivity and imaginative capacity concerning vulnerabilities, new designs or improvements to existing designs can be introduced, improving the ability of individuals and organizations to counter vulnerabilities. Social and institutional ignorance (Bijker 2006, 59) that can put systems at risk can be countered by articulations of vulnerability, since these create the logical framework for adaptation and mitigation in the face of potential hazards (Green & McFadden 2007, 1027).

[8] '20/20' denotes vision of normal acuity, as measured by the ability to read a chart at a distance of 20 feet. The phrase 'hindsight is 20/20' means that it is easy to be knowledgeable about an event after it has already happened.

Attention to the various causes of vulnerabilities could enable more proactive measures rather than reactive ones, for example in the form of foresight or structural solutions that are implemented before a potentially harmful perturbation. The systemic approaches to vulnerability and drift discussed above show the necessity of delving deeper beyond the surface of established routines. However, analyses of vulnerability can be compromised by the fact that risks tend to turn more heads in a political context since they are (supposedly) quantifiable and measurable, and that providing structural solutions to vulnerabilities is difficult to justify on economic grounds.

Resilience

Studies of vulnerable components of socio-technical systems have found a great deal of appraisal among scholars working in the field or organization studies, and have led to the establishment of the so-called 'High Reliability Theory' (e.g. Roberts 1990; Bigley & Roberts 2001; Sheffi 2005; Roe & Schulman 2008). Whereas proponents of Perrow's Normal Accidents Theory claim that interactional complexity and tight coupling will lead to inevitable or 'normal' accidents, adherent of the High Reliability Theory will claim that systems cannot only be made safer, but also more 'resilient'. Resilience describes the ability of individuals, organizations, and sociotechnical systems to recover from disruptions.

Resilience is not always seen as a beneficial property of individuals, organizations, and sociotechnical systems. Gallopín (2006) points out that resilience can be problematic if it signifies the capacity to return to an original state, since this state was the source of vulnerability in the first place. Resilience and vulnerability are therefore not simply antonyms:

> "[A] resilient system is less vulnerable than a non-resilient one, but this relation does not necessarily imply symmetry […] the flip side of vulnerability would be a concept that denotes capacity to maintain the structure of the system against perturbations, even if its resilience is overcome. Robustness is a good candidate." (Gallopín 2006, 299-300)

The problem with robust systems, Gallopín argues, is that they are also insensitive: "[s]ensitivity may open a system to threats, but an insensitive system may be unable to adapt and seize opportunity." (Ibid. p. 300)

For this reason, Gallopín introduces the idea of 'adaptive capacity', which refers to the ability of individuals, organizations, and systems to adapt to (a range of) contingencies, and thereby improve their ability to withstand perturbations. In the field of climate change, adaptive capacity refers to "the ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences." (IPCC 2001, quoted in Gallopín 2006, 300) Adaptation is defined as "adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates, harms, or exploits beneficial opportunities." (Ibid.) An important difference between adjustments and adaptations is that the latter term usually signifies more profound and structural changes than the former. Adaptive capacity can be seen as a more elaborate antonym of vulnerability, since it addresses the potentially harmful effects of robustness and insensitivity.

Woods proposes a definition of resilience that includes a stronger emphasis on the ability of systems to learn how to cope with perturbations. According to Woods,

> "the broader capability resilience is concerned with monitoring the boundary conditions of the current model for competence (how strategies are matched to demands) and adjusting or expanding that model to better accommodate changing demands. The focus is on assessing the organization's adaptive capacity relative to challenges to that capacity." (2003, 22)

Woods argues that all systems adapt, which makes it necessary to reserve the term resilience for "the broader capability – how well can a system handle disruptions and variations that fall outside of the base mechanism/model for being adaptive as defined in that system." (Woods 2006, 21) Woods' definition of resilience stresses the ability of a system to respond to disruptions that fall outside of its immediate scope, and thus does not correspond neatly to Gallopín's criticism pertaining to robustness and insensitivity. I will refer to Gallopín's problematic version of resilience as 'stubbornness', and reserve the term 'resilience' for the more reflexive and adaptive approach suggested by Woods. However, Woods' work on resilience, which can be categorized under the broader category of 'resilience engineering' (e.g. Hollnagel et al. 2006), can be problematized as well. Proponents of both High Reliability Theory and resilience engineering consider vulnerabilities as aspects of technological systems that can be ruled out by means of a tried and true "measure and manage approach to safety", all the while ignoring "the cultural context of safety issues." (Healy & Mesman, forthcoming)

More generally, it is questionable whether vulnerability can be ruled out altogether. Our understanding of sociotechnical systems is certainly not complete, nor can we rule out that solutions developed today will not render sociotechnical systems susceptible to risks tomorrow. The dominant approach to potential hazards is still technoscientific and thorough studies of sociotechnical systems are not embraced universally, which makes it possible that a previously unknown or ignored vulnerability will turn up sooner or later. Finally, as indicated by Wackers and Kørte (2003), sociotechnical systems may strive for performative closure, which may induce blind spots and drifts that remain veiled, at least for the time being. Even Woods, whose work was discussed above, suggests a number of challenges that cannot be overcome easily. Patterns that emerge regularly in resilience engineering are:

> "Drift toward failure as defenses erode in the face of production pressure; an organization that takes past success as a reason for confidence instead of investing in anticipating the changing potential for failure; fragmented problem solving that clouds the big picture; failure to revise assessments as new evidence accumulates; breakdowns at the boundaries of organizational units that impede communication and coordination." (Woods et al. 2010, 88)

Aside from the questionable idea that vulnerability *can* be ruled out, it is not self-explanatory it *should* be ruled out either. Within technological cultures, the state of being vulnerable may have beneficial effects, and should therefore not be seen as an exclusively negative characteristic: some measure of vulnerability may be crucial in order to maintain a certain level of flexibility, innovation, and social learning in society. This entails a process where the study of vulnerability can allow a technological culture to become more resilient to risks, provided it seizes the opportunity to learn, innovate, and acquire new knowledge. As indicated above Law (2000) and Wackers and Kørte (2003) would even claim that some level of risk-taking is required for a system to function smoothly and efficiently. According to Bijker, "conceptions of vulnerability fall in two classes, depending on whether their opposite has a connotation of control (such as in security) or flexibility (such as in resilience)." (2006, 67) Full control is not desirable, since "to live in an open, changing, and innovative culture, we must pay the price of vulnerability." (Ibid. p. 52)

Reasons for studying technological cultures in terms of 'vulnerability'

Studying the use of simulations and models in terms of vulnerability has a number of advantages. First, the concept of vulnerability enables a thorough study of how knowledge about risks is produced by means of simulations and models. Studying vulnerability requires looking beyond risks that are acknowledged by various practitioners in the field, and needs to delve deeper into the processes whereby knowledge about risks is produced, i.e. by inquiring into simulations practice and its materiality[9], as well as the institutional and socio-political context of simulation practice. Vulnerability can function as an investigative concept by means of which simulation practice can be pried open (see also the discussion on routines and programs in studies of vulnerability).

Second, the notion of vulnerability allows me to ask how simulations and models may put technological cultures at risk. Established routines and programs may not consider the use of simulations and models as something that puts technological cultures at risk, but the aforementioned thorough analysis of simulation practice could (at least in principle) enable a different view. Vulnerability provides a perspective on how individuals, organizations, and sociotechnical systems are at risk, without that risk actually occurring. I do not embrace simulations and models as an unconditionally beneficial component of technological cultures, nor do I denounce them by means of sweeping claims of a supposedly dismal influence of technologies on today's society, or gloomy prospects of a looming cataclysm caused by irreversible technologies. Rather, I aim to assess the impact of simulation practice more rigorously using a social constructivist framework in a manner that is faithful to the use of simulations and models in the field.

Third, by approaching simulation practice in terms of vulnerability, I stress the points made above about the role of susceptibility to harm and the related possibility of innovation and learning. The question is whether technological cultures can tap into the possibilities afforded by their vulnerable state, rather than abolishing their vulnerability altogether. In other words, I do not propose a 'new and improved' form of simulation practice that will once and for all cancel out vulnerabilities, since this reinforces

[9] Beck is accused of taking a primarily macro sociological approach to risk that shies away from approaching the process of producing knowledge about risks (e.g. van Loon 2002, 45ff.).

hegemonic ideas pertaining to the possibilities of technological innovation that can potentially lead to robustness and insensitivity.

1.3 Research strategy and methodology: an ethnography of engineering

In order to understand the relationship between simulations and models on the one hand, and the Netherlands (seen as a vulnerable technological culture in the aforementioned sense), this book unravels the seamless webs of technological, institutional, political, economic, and cultural aspects related to simulation practice. As I argued above, vulnerability is a property of individuals, technological artifacts, organizations, and sociotechnical systems that can be approached in different ways. As a concept that helps to scratch the surface of sociotechnical practices, vulnerability leverages an understanding of how technological cultures are put at risk, which may provide a way to counter vulnerabilities. I use vulnerability primarily as an 'analysts' concept' rather than an 'actors' concept' (Collins & Yearley 1992), with the aim of understanding how simulation practice may put technological cultures at risk. However, the notion of vulnerability does occasionally surface in debates around water management. If this should be the case, I point out explicitly the use of the concept of vulnerability by actors rather than myself.

The simulations and models that are used to engage risks in water management in the Netherlands are subject to what has been called 'interpretative flexibility' (e.g. Pinch & Bijker 1984; Bijker 1995a), which indicates that the meaning of these technological artifacts is subject to different explanations. Wartofsky (1979, quoted in Beaulieu et al. 2011) describes a "muddle" of models in science, which can be characterized by "a proliferation of strange and unrelated entities which come to be called models." (Wartofsky 1979, 1) Different practices can be categorized by the colloquial terms 'model', 'modeling', and 'simulation', which is due to the myriad of actors that use simulations and models and their divergent agendas. Rather than boiling down the various practices pertaining to water-related risks and simulation practice to neat and clear-cut definitions, I engage simulation practice to indicate how risks, simulations, and social actors interact and lead to forms of simulation practice that are sustainable over time. Rather than affirming manifold meanings and diversity, I show how coherent concepts and practices emerge. As Hine has argued, such a focus

> "sidesteps the position of characterizing the world as inherently complex, or objects as inherently multiple, and reasserts the [Science and Technology Studies] sensitivity to symmetry, by offering the possibility that both complexity and coherence could be situated achievements rather than straightforward matters of fact." (Hine 2007, 664)

In order to understand such 'situated achievements', I decided to conduct an ethnographic study of simulation practices in water management in the Netherlands. Ethnography is a research method that privileges observation as its main source of information, often complemented by (informal) conversation, interviewing, and written and/or visual material (e.g. Hess 2002; Crang & Cook 2007; Gobo 2008). Depending on whether they actively participate in their field of study, ethnographers engage in either participant observation or non-participant observation. Due to my own lack of expertise in modeling, I conducted non-participant observation. As I stressed in the acknowledgements already, I am very grateful to the engineers at Deltares and other institutions and companies for their willingness to share their knowledge. In the case of events that transpired (long) before my presence in the field, I sometimes needed to rely on secondary sources on simulations and models, historical studies of engineering in the Netherlands, notes of meetings, and policy documents. The combination of observation, interviewing, and document analysis enabled me to study the 'design worlds'[10] in which engineers, computer programmers, managers, policy makers, and decision makers collectively engage various water-related risks. Thus, I approached the design worlds populated by the aforementioned social actors as "the result of individuals drawing on the structures of their 'culture', rather than these structures being seen as, somehow, existing 'outside' the mundane spheres of their everyday action and knowledge." (Crang & Cook 2007, 7)

Ethnography comes with a set of difficulties (Ibid. p. 7-8). First, there is no such thing as a detached researcher who can simply 'read' the life world of his or her subject. My experiences in the field were circumstantial by default, simply because I happened to be present in the field at a particular point in time. Admittedly, computational modeling can be difficult to analyze for the ethnographer due to a lack of knowledge about the

[10] In her ethnographic study of architecture, Yaneva approaches her subject "as a co-operative activity of architects and support personnel alike, humans and models, paints and pixels, material samples and plans, all of which constitute the *design world*." (Yaneva 2009, 12, original emphasis)

underpinnings of simulations and models. Work carried out behind computer screens (by far the most dominant form of simulation practice I encountered) tended to withdraw from my ethnographic gaze: many interviewees preferred to discuss their work in a face-to-face interview. As an ethnographer observing simulation practice on computer screens I was rather present or visible to those involved. In my case, this led to elaborate explanations of simulation practice by the social actors I was observing to ensure I understood their work. In some cases, this also led to the desire of social actors to 'perform' in a certain manner, for example by sharing personal ideas about simulation practice and anecdotes. I also felt that some social actors wanted to ensure the time I spent with them was valuable in the larger scheme of my research. In sum, I could not simply take a seat and expect my research subjects to go about their daily routine.

A further complication of my ability to study simulation practice is my background and scholarly commitment to Science and Technology Studies (STS) and philosophy of science and technology, which have undoubtedly shaped my interactions with practitioners in the field. My aforementioned lack of knowledge about simulation practice may have compromised the depth of my analysis. However, I do think I carried out a substantial study of the field by basing my findings on observations, interviews, and documents. In addition, rather than proclaiming some ultimate and all-encompassing perspective on simulation practice, I argue that interactions between practitioners and non-practitioners can be beneficial, especially if the latter can contribute their own perspective and reflections. Despite more attention for societal issues, water management in the Netherlands can be described as predominantly engineering-oriented, which is due to its still dominant technocratic past (Merkx 2007, 17). Societal issues are often identified, though interdisciplinary research that acknowledges the importance of both engineering and the social sciences hardly takes place (Merkx et al. 2007). In such an environment, contributing a sociological and philosophical perspective on simulation practice ensures reflexivity: research from an STS perspective can contribute a perspective on simulations and models that appears to be absent in the field.[11] The value of the welcoming attitude with which my research was encountered in the field cannot be emphasized enough here.

[11] A recent project named 'Building with Nature' is explicitly aimed at incorporating socio-political demands into the realm of hydraulic engineering, and thus indicates practices that go beyond a purely technocratic approach.

A second issue related to ethnography is that it can assume the actors it studies to be transparent carriers of uncontested cultural codes. Due to my unfamiliarity with the field of water management, my own ethnographic work required a great deal of research into the subject area, which was augmented by the expertise of the people I studied. I believe the alignment of their ideas with written material on simulation practice has enabled a sufficiently thorough perspective on my part.

A third issue that can arise in ethnographic studies is that they assume the cultures they study to be isolated and homogenous. I have approached a variety of actors (e.g. engineers, computer programmers, managers, decision makers, and policy makers) from a variety of organizations (research institutes, engineering consultancies, educational and governmental institutions). This enables a thorough perspective by means of which different ideas and opinions can be compared.

Fourth and finally, ethnography is occasionally considered to be a mere 'subjective' and 'relativistic' method (Crang & Cook 2007, 8). In response to this issue, I refer to the work of Hekman, who rejects "the definition of knowledge and truth as either universal or relative in favor of a conception of *all knowledge* as situated and discursive." (Hekman 2004, 234, emphasis mine) Rather than pursuing a quest for truth or falsity, I focus on processes of knowledge production by studying the various material, institutional, and socio-political aspects that shape the production of knowledge about water-related risks. Although this book focuses on water management in the Netherlands, I aim to specify more general issues related to the role of simulations and models, primarily in terms of how simulation practice can induce or exacerbate vulnerabilities. The concluding chapter of the book contains a generalization of my findings, and shows how they can be used in other forms of simulation practice.

Case study design: construction, validation, communication

In order to understand the relationship between the vulnerability of the Netherlands, seen as a profoundly technological culture, and the use of simulations and models in water management in the Netherlands, my ethnographic approach to water management looks at three aspects of simulation practice: construction, validation, and communication. My first case study focuses primarily on the construction of simulations and models by looking at the formalization and subsequent study of water-related risks in simulation practice. My second case study looks mainly at the process of validation (the process of ensuring a model correctly represents phenomena in reality, which is explained in more detail in section 2.2 and chapter 4), and subsequent attribution of explanatory power to models. Finally, in my third and final case study, I look at how simulations and models are designed as platforms for communication between various social actors, and how simulation practice shapes the actions of these different social actors. These three aspects of simulation practice cannot be distinguished completely, and in fact often cross over into each other. For example, the process of model construction often also entails model validation in order to find out whether and how a given model needs to be improved. Rather than positioning these case studies as fully self-contained, I chose to adopt the differentiation between construction, validation, and communication to create focal points on different issues pertaining to simulation practice that may put technological cultures at risk.

Introducing the empirical domain: water management in the Netherlands

The majority of my ethnographic study was conducted at Deltares, an institute for applied research in the domains of water, subsurface, and infrastructure that is located in *Delft*, the Netherlands. The city of *Delft* is a hub for internationally renowned research in the field of industrial design, architecture, and engineering, and many students of the Technical University Delft (TUD hereafter) find their way to Deltares due to thesis-related projects, which frequently leads to employment. Deltares was formed in 2008 through a merger that involved Delft Hydraulics (known in Dutch as *Waterloopkundig Laboratorium*, which was a partly government-funded applied research institute in hydraulic engineering and water management that was founded in 1927; see Chapter 3), GeoDelft (a similar institute in soil mechanics and geotechnical engineering, founded in 1934), the shallow subsoil component of the former Netherlands Geological Survey, by that time part of TNO (the Netherlands Organization for Applied Scientific Research), and individuals involved in hydraulic and geotechnical research from specialist departments of *Rijkswaterstaat* (an agency of the Netherlands Ministry of Infrastructure and Environment, responsible for implementing the government's policies concerning water- and transport-related infrastructures). Important drivers for this merger were a thorough reorganization of the infrastructure of applied research, which was meant to eliminate false competition by government-funded applied research institutes within *Rijkswaterstaat*, and the desire to unite the expertise necessary to enable sustainably living and working in the Netherlands and similar low-lying deltaic areas in one institute (Wijffels et al. 2004). The empirical material will feature the challenges Deltares has come to face due to its role in present-day technological and socio-political contexts, such as adaptation to environmental circumstances, flood protection, and commitments to participatory forms of governance.

In addition to the material I collected at Deltares, I conducted additional interviews and made observations at educational institutions, engineering consultancies, governmental bodies, and symposia on water management in the Netherlands. The majority of the interviews and observations were carried out between March 2009 and July 2009, with additional shorter visits to the field and interview sessions later in 2009, 2010, and 2011. I conducted a total of 73 interviews with engineers, ecologists, marine biologists, decision makers, policy makers, managers, researchers, academics, and software developers (see Appendix on page 235). Two of these interviews were conducted in English, the remaining 70 in Dutch. Although I can claim proficiency in English to some extent, I take full responsibility for the translation of interview excerpts included here to English.

The three case studies cover a substantial part of Deltares' activities. The first case study looks at how the materiality of modeling in hydrology (the science of the properties, distribution, and effects of water on the earth's surface) and hydrodynamics (the science of the dynamics of fluids) has changed since the early 20th century. In these two related disciplines, simulations and models enable the study of factors influencing inundation and the influence of water movement on coastal structures (among other topics). The second case study covers model validation in the field of geotechnical engineering, where simulations and models are used to study and predict dike failure mechanisms, but increasingly also as a means to prepare for evacuations. The third and final case study looks at the use of models by software developers, ecologists, decision makers, and policy makers. I study the development of a model aimed at water quality governance in the context of the implementation of European policies aimed at improving water quality and ecological sustainability. These three case studies concern forms of simulation practice that cannot be distinguished neatly from each other, but rather serve as complementary examples of modeling communities at Deltares, where the members of different 'modeling communities' often interact.

The following overview can now be presented, which shows the three case studies, the aspect of simulation practice discussed in each of them, the accident in question, and the vulnerabilities that I present on the basis of my case studies (table 1.1):

Case study	Hydrology and hydrodynamics (Chapter 3)	Geotechnical engineering (Chapter 4)	Ecology (Chapter 5)
Central aspect of simulation practice	Construction	Validation	Communication
Potential accident	Flooding, failure of coastal structures	Dike breach and subsequent flooding	Ecological deterioration
Vulnerability	Discussed in chapter 3	Discussed in chapter 4	Discussed in chapter 5

Table 1.1 Overview of the three case studies in this book

Before presenting my three case studies, I first provide an overview of studies of simulation practice in the following chapter, which is devoted to the aforementioned mediating role and inscriptive effects of simulations and models.

2. Simulation epistemologies

Introduction

In this chapter, I study various definitions of both simulations and models in more detail, and show how these two concepts are said to differ. I also elaborate on claims that simulation practice implies novel forms of scientific practice. Second, I look at epistemological issues related to simulation practice. Simulations and models can be explained in a straightforward sense as simplifications of a more complex reality, but on closer inspection reveals representational work that leads to issues concerning empirical adequacy and reliability. Finally, I look at critical approaches to simulation practice. I conclude the chapter by describing how I analyze simulation and models in chapters 3, 4, and 5, and why I think this approach is most fruitful to assess the relationship between simulation practice and vulnerability.

2.1 Framing models, simulations, and experiments

Models are used in numerous scientific disciplines in both natural and social sciences, and also play a prominent role in applied sciences, such as engineering, materials sciences, and bioinformatics. The term 'model' can be understood as a noun, adjective, and verb (Ackoff 1962, 108, quoted in Healy 2008, 7). The noun 'model' denotes a simplified representation or description of a system. Models aim to capture characteristics of systems that are considered to be essential or fruitful for further study of those systems. The term 'system' describes a particular object (from insects to architecture) or processes (e.g. meteorological phenomena, such as the formation of clouds) that are the subject of analysis. Models can be physical (e.g. scale models of buildings). In such cases, a model "denotes a thing, whether actually existing or only mentally conceived of, whose properties are to be copied." (Boltzmann 1974, 213) However, models can also be conceptual, e.g. a verbal description of a system or a set of equations describing the dynamics of a system. The adjective 'model' describes an ideal, such as a 'model husband' or 'model wife'. Finally, the verb 'to model' describes the activity of demonstrating or revealing by capturing properties that are considered to be conducive to the understanding of those using the model.

Modeling is necessary in case a problem or system needs to be studied, yet where it is not possible to experiment with the actual system. The latter may not be amenable to experimentation because of a lack of knowledge of the system in question. A crucial aspect of modeling is that it is used in cases where there is a tentative understanding of certain phenomena, or even a lack thereof. Models may yield an understanding of the problem at hand, and the premises on which their formation is based will often be revised in the process. In this context, Sismondo defines models as "systems standing in for the unruly or opaque, though also for the incomplete." (Sismondo 1999, 248) Furthermore, experimentation may not be possible in a practical sense. For example, one could decide to conduct a scientific study of the global climate, and although some interventions are possible on a global scale (a guiding premise of the scientific discipline known as geoengineering, which should not be confused with geotechnical engineering that is the subject of chapter 4), the practical implications and potentially disastrous repercussions of experimentation on a global scale preclude its realization in practice.

Either a physical model or a mathematical model of systems may be constructed through a process of simplification and/or formalization. In the case of mathematical models, systems can be formalized as a set of equations. Models rely on abstractions and/or idealizations. Morrison (1999, 38) describes abstractions as representations of systems that omit certain properties of those systems. An idealization is a characterization of a system where properties of the latter are deliberately distorted, which precludes their ability to describe their actual counterparts. Batterman (2009) argues idealization is an inescapable part of modeling. In fact, abstraction and idealization are required for successful use of simulations and models in practice: "[m]odeling each aspect of the system will seldom be required to make effective decisions, and might result in excessive model execution time, in missed deadlines, or in obscuring important system factors." (Law 2007, 246) This immediately introduces the question whether a given model accurately and reliably reflects the system studied through modeling.

In some cases, conceptual models may be solved 'analytically' by finding

> "a solution to the set of equations that make up the model. For this purpose, calculus, trigonometry, and other mathematical techniques are employed. Being able to write down the solution this way makes one absolutely sure how the model will behave under any circumstance."[12] (Grüne-Yanoff & Weirich 2010, 26)

[12] Analytically solving an equation in this provides knowledge about the model's behavior, but is restricted to specific initial values and boundary conditions chosen by those solving the model in the manner described. As a result, the solution applies to these initial values and boundary conditions, and not "under

However, the complexity of equations underlying models cannot always be solved analytically. Take for example the turbulent movements of water near a coastal structure, the dissipation of heat in an engine, or the dynamics of trade in economic systems. Such target systems are constantly changing. In mathematics, derivatives describe rates of change. Differential equations describe the differential of a quantity, in other words, how rapidly the aforementioned quantity changes with respect to the change in another quantity. Differential equations contain derivatives of a variable.[13] Many differential equations may not be analytically solvable due to their complexity. In such cases, simulations can be used to engage such complexities, provided 'discretization' is carried out. The term can be defined as

> "the process by which simulationists turn differential equations, which relate continuous rates of change over infinitesimal intervals, into difference equations, which relate rates of change over finite, or discrete, intervals. The values that these difference equations give can then be calculated by a digital computer, from one discrete moment in time to the next." (Winsberg 2010, 8)[14]

Many real-world systems are characterized by a high degree of complexity that is caused by the number of interacting elements. Technical literature on simulations and models stresses the sheer complexity of equations underlying models of such real-world systems and the large quantities of data that are fed into models in order to study dynamic behavior of systems. However, as much as the complexity of certain models requires the use of simulations, these models also need to be incorporated into the environment of the computer: "in a simulation, we use a computer to evaluate a model *numerically*, and data are gathered in order to *estimate* the desired true characteristics of the model." (Law 2007, 1, original emphasis) The emphasis on estimation here is important, since a simulation will be based on a model: "[s]imulation allows one to estimate the performance of an existing system *under some projected set of operating conditions*." (Ibid. p. 76, my emphasis) In sum, a simulation can be seen as an application of a model that allows

any circumstance" (Grüne-Yanoff &Weirich 2010, 26) as is suggested here. My thanks to Huib de Vriend for clarifying this matter.

13 I cannot venture deeply into a mathematical explanation of differential equations. For a more elaborate explanation of differential equations with respect to modeling, see Humphreys 2004, pp. 60-7.

14 Winsberg (2010) and Petersen (2012) use the term 'simulationist' when speaking of scientists, engineers, and other social actors who engage in the development and/or use of simulations and models.

the model to represent dynamic properties of its target system. However, this application requires considerable effort on the part of those developing and using the simulation in question, for example discretization or converting differential equations into difference equations (see Winsberg, op. cit.).

Humphreys' definition of computer simulations echoes the aforementioned issues of computational complexity and analytical insolvability: "[a] computer simulation is any computer-implemented method for exploring the properties of mathematical models where analytical methods are unavailable." (2004, 107-8) Humphreys argues computer simulations provide important means of access to phenomena incomprehensible to human minds, which is due to the computational complexities underlying most (but not necessarily all) computer simulations. Perhaps humans could perform such equations in principle, but in practice this will often be impossible or at least problematic (see section 3.1). Humphreys characterizes the cases where the analytic solvability of models is precluded to computers and outside the cognitive scope of human agents as 'epistemically opaque' (Humphreys 2009a; see also Grüne-Yanoff & Weirich 2010, 26). This notion of 'epistemic opacity' will play a more prominent role in chapter 3. The human sensorium can be extended by means of computer simulations, since the latter provide an understanding of events taking place in expanded time frames (e.g. how did the global climate evolve over the past 100 years?) or hypothetical states of affairs (e.g. will the North Sea threaten Dutch dikes if water levels will rise by two meters in the next 50 years?).

Although Winsberg, Law, and Humphreys speak mostly about *computer* simulations, the term 'simulation' can be understood in more general terms as imitation or replication. Banks defines simulation as

> "the imitation of the operations of a real-world process or system over time. Simulation involves the generation of an artificial history of the system and the observation of that artificial history to draw inferences concerning the operating characteristics of the real system that is represented." (1998, 3)

According to Hartmann, "*simulation imitates one process by another process*. In this definition, the term 'process' refers solely to some object or system whose state changes over time. If the simulation is run on a computer, it is called a *computer simulation*." (1996, 83, original emphasis) I adopt Hartmann's generic definition of simulation with the proviso that his reference to 'imitation' also leads to the question how the similarity between a simulation and its target system can be understood. In the following section, I point out why this emphasis on imitation requires more explanation, but for now the previous definitions of simulations provide sufficient bearing. A simulation is run in order to produce output in the form of observable phenomena (in the case of a physical simulation) or data (in the case of a simulation that is based on an mathematic or abstract model). This data is sometimes also visualized. Although the term 'simulation' will often invoke futuristic images, simulations are by no means synonymous with visualizations.[15]

The definition of simulation is by no means restricted to computer simulations, but also applies to physical forms of simulation carried out with scale models. Scenarios deployed for the purpose of training personnel (e.g. flight simulators and so-called 'serious games') are often also defined as simulations. Such simulations concern the enactment of critical situations in order to prepare for wars or emergencies, and will often involve the use of various artifacts, costumes, makeup, and other kinds of smoke and mirrors to create a depiction of a situation that is considered to be 'realistic'. Simulations can be distinguished in several ways. A simulation may be based on physical objects (scale models) or abstract objects (a conceptual model, such as a set of equations describing the behavior of water near coastal structures). In addition, simulations based on abstract objects can be distinguished by their dynamics: some use discrete dynamics, which represents the chronological development of a system in sequential steps, while others use a continuous dynamics.

Based on the previous discussion, some differences between simulations and models need to be pointed out. First, though simulations are based on models, the former have a temporal dimension whereas the latter do not. In fact, the ability of simulations to 'run' is a crucial part of their usage. Second, whereas models can (in some cases) be solved analytically, simulations most often cannot, which is related to the epistemic opacity established by computational complexity and intractability, which were discussed above.

Simulations cannot simply be conflated with experiments since both can have different targets. Gilbert and Troitzsch (2005, quoted in Grüne-Yanoff & Weirich 2010, 27) claim experiments concern the very object of study, while simulations deploy models of the object of study rather than the object itself. Grüne-Yanoff and Weirich (Ibid.) also

[15] Chapters 3 through 5 will elaborate on the various roles of visualizations and visual representations of model output.

refer to the work of Guala (2005), who maintains that experiments rely on material correspondence between the experimental setup and the target system, while the correspondence between simulations and their targets is strictly formal. As will become clear in section 2.3, claims that an experiment can bear direct semblance to its object of study are highly suspect in STS, where experiments are seen as staged interactions between phenomena that do not automatically speak for the target systems they are meant to represent. For example, researchers may be interested in the relationship between the movement of water and the growth of reeds. Great effort is put into building an experimental setup that matches the conditions in the actual system, for example by making sure that the experimental setup corresponds with the movement of water, types of soil, species of reed, and temperatures encountered in the system 'out there'. Note that this experimental setup already suggests a form of modeling: a more complex reality is simplified in such a manner that particular properties that are the subject of interest are isolated, and can subsequently be studied. This is not to say that models are always experiments, but the reverse can apply in the sense that experimentation relies on the aforementioned definition of the verb 'to model' – to reveal by means of abstraction. Formally speaking, the reed experiment and its real counterpart share material properties, but the outcome of the experiment will ultimately rely on the conditions of the experimental setup, measurement, and processing of data. Petersen (2012, 174) engages the work of authors who have drawn similarities between experiments and computer simulations by characterizing the latter as experiments on theories (e.g. Galison 1996; Dowling 1999; Keller 2003; Morgan 2003). Still, Petersen strictly separates computer simulations from experiments by stressing that the former involve mathematical objects, while the latter involve material objects, and that both forms of scientific practice require different skill sets (Winsberg 2009; Petersen 2012, 46).[16] In my view, the difference between simulations and experiments appears to be a grey area. For example, engineers may define trial runs with a numerical model as

[16] Parker (2009) argues that computer simulations should be seen as material experiments, since they involve the manipulation and observed behavior of material and physical systems, namely programmed digital computers. Although Parker is correct in pointing out the importance of the materiality of computer simulations, it is not accepted unanimously that materiality is important in explaining the relationship between computer simulations and their target systems. Computer simulations have no direct interaction with their target systems. Barberousse et al. claim explanations of how and why computer simulations provide information about their target systems can only proceed by 'semantic analysis': "showing how the physical states of the computer can step after step be interpreted as computational states, as values of variables and finally as representations of the target system's successive states."(2009, 558) The fact that a computer simulation is a physical process in some sense does not yet provide an exhaustive explanation of its relationship with its target system.

'experiments'. In addition, simulations may deploy material models and thus are not restricted to computer-implemented methods.

Does this mean there is nothing distinctly new about simulation practice? Various authors have stressed the novelty of computer simulations, and claim simulations and models herald an increasingly computational orientation of the sciences in general that requires a new approach to studying simulation practice (e.g. Rohrlich 1991, quoted in Grüne-Yanoff & Weirich 2010, 28; Winsberg 2010; Gramelsberger 2010 and 2011). However, the idea that simulations and models imply an 'epistemic shift' (Heymann 2010, 194), perhaps of paradigmatic proportions, is not shared unanimously. Frigg and Reiss (2009) maintain that the metaphysical, epistemic, semantic, and methodological issues supposedly raised by computer simulations can all be subsumed under already existing discussions in the philosophy of science. Humphreys (2009a) has explicitly addressed these claims, and describes how the epistemic opacity and dynamic properties of computer simulations do pose new issues. Moreover, issues related to discretization and the computational resources needed to carry out calculations needs to be taken up as well, since they cannot be accommodated by current analyses of scientific models.

As much as this may frustrate the reader looking for a neat exposition of the terms 'model', 'simulation' and 'experiment', I wish to do justice to the more muddled myriad of definitions of simulations and models that can be found in simulation practice (see also the work of Wartofsky mentioned in section 1.3). I therefore pay close attention to how practitioners speak of models, simulations, and experiments. As will become clear, the terms 'model', 'simulation', and 'experiment' are used rather loosely and often interchangeably. Without wanting to reduce simulation practice to a Wittgensteinian language game, engineers will refer to models, simulations, experiments, and simulation-models (in Dutch: 'simulatiemodellen') when talking about their use of simulations and models in their day-to-day activities, sometimes sticking to a single term but often using multiple terms. I will generally use the more inclusive phrasing 'simulations and models' to refer to the object of simulation practice. However, I explicitly refer to either simulations or models in case publications or interviewees do so. In addition, I adopt the term 'simulationists' (Winsberg 2010, 8; Petersen 2012, 4) when speaking of scientists, engineers, and other social actors who engage in the development and/or use of simulations and models.

2.2 Representation or heuristics? Functions of simulations and models

According to Gilbert and Troitzsch (2005, 4-6), simulations have multiple functions that include facilitating understanding of systems, prediction, functioning as a substitute for human capabilities, training, entertainment, discovery, and formalization. As became clear, simulations and models are based on processes of abstraction and idealization, which allows them to fulfill these functions. Thus, scientists, engineers, and other practitioners are able to

> "capture certain essentials […] at worst, a model is a concise description of a body of data. At best, it captures the essential physics of the problem, it illuminates the principles that underline the key observations, and it predicts behavior under conditions which have not yet been studied." (Ashby 1996, 95)

How are simulations and models created so that they may capture the aforementioned 'certain essentials', and what is the impact of the abstraction, simplification, and idealization on which simulations and models rely?

Representational work

Modeling, defined above as the process of revealing through abstraction, requires considerable effort on the part of simulationists, which can be illustrated by a brief description of the stages of modeling practice.[17] A first step involves the definition of the problem and creating a conceptual model (e.g. 'back of the envelope' sketches that are based on expertise and intuition). A target system can be represented by means of a diagram that aims to capture the behavior of the system (e.g. a diagram that depicts the inner workings of machinery). Computer simulations make use of schematizations that express target systems as grids or interacting nodes, thereby making the complexity of the target system amenable to computation. Figure 2.1 shows an example of a schematization, which allows the target system in question (the *Waddenzee*) to be modeled as interactions between points on a grid. Other schematizations may represent target systems as nodes in a network, which is another form of schematization. The cells in the

[17] The following is based on technical literature on simulation practice, in particular the descriptions of simulation development and implementation and flow diagrams that illustrate the various stages of the development of simulations in Banks (1998, 16) and Law (2007, 67). My description of model development and implementation is not intended to be exhaustive, but should rather make the reader aware of the representational work that needs to be carried out by simulationists.

grid shown on figure 2.1 have different sizes: hydrological and hydrodynamic phenomena near the coast feature turbulence, which is a complex phenomenon that needs to be modeled by means of a high resolution (and therefore fine) grid. A lower-resolution grid would simply gloss over the complexities of interacting flows. On the open sea, hydrological and hydrodynamic phenomena are relatively straightforward in comparison with those near the coast, enabling a coarse model grid. Simulationists will carefully balance the task at hand with computational requirements. The availability of computational power does not always mean that simulationists will make the resolution of their schematizations as high as possible. I will elaborate on this in more detail in the next chapter.

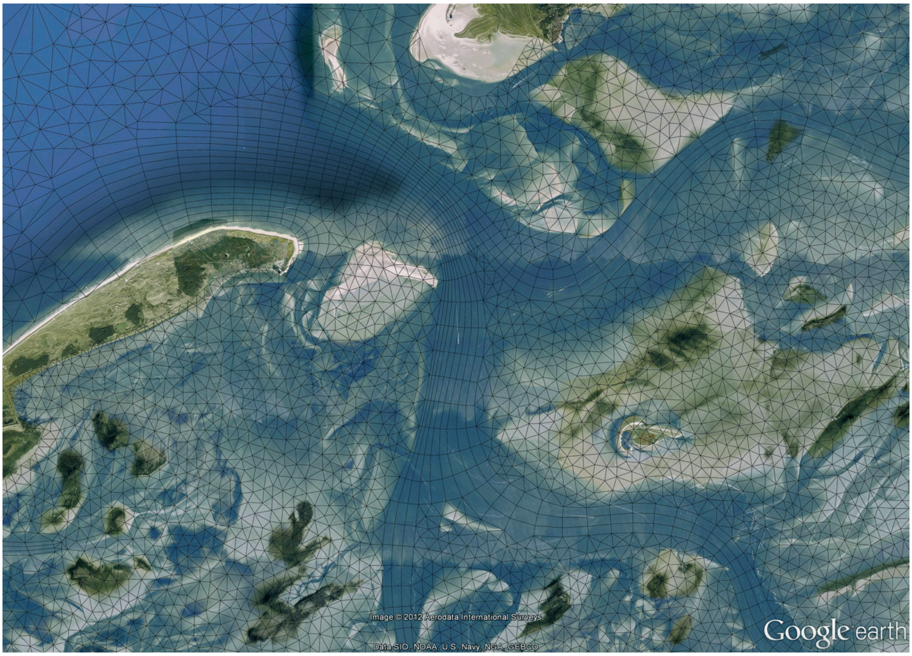

Figure 2.1 Unstructured Wadden Sea grid for use in DFlow-FM model of Deltares. © 2012 Google.

In the case of computer simulations, input data can now be collected. This stage involves the acquisition, parsing (ordering data into elements that can be processed or discrete events), and filtering (removing data considered to be irrelevant, also known as 'noise') of data, and in some cases also data mining (using insights from mathematics, statistics, and artificial intelligence to discern patterns in data). Subsequently, either software or physical models are developed, and pilot runs are carried out. Simulationists will then determine the validity of the model by determining whether the output model in question corresponds with the observed behavior of the target system, though this may be exceptionally difficult in those cases where this behavior is hard or impossible to access (e.g. in the case of hypothetical scenarios). In such cases, simulationists may have to rely on data about the system's past behavior, or knowledge based on similar models and systems. By means of calibration (modifying input parameters of a model until the model output matches some observed set of data) simulationists will check the accuracy of a computer-implemented model, making adjustments to their calculations where necessary. Computer-implemented methods will also carry out a process of verification used to make sure the model is built and performs correctly. Based on the operational validity, the model, problem space, and (in the case of computer simulations) software may be revised and subject to further testing. The cycle of verification and validation may need to be carried out multiple times. Once the experimental design of the model functions satisfactorily according to simulationists, the model will be run, in some cases using a variety of input values (e.g. in the case simulationists are interested in the behavior of a system under different circumstances). The model's output will then be analyzed, resulting in the documentation, presentation, and implementation of results.

Representation, empirical adequacy, and reliability

The foregoing remarks notwithstanding, Beaulieu et al. (2011) stress that discussions on simulations and models often ignore the representational work of simulationists. Modeling practices have a degree of variability due to personal preferences and expertise (Becker et al. 2005). This variability does not only apply to modeling practices, but can be applied to data collection (e.g. measurement, observation) as well. A focus on the commitments of simulationists will lead to a more detailed understanding of how simulations and models function, and the expectations that accompany their functioning. This interpretation roughly corresponds with a more general attitude towards scientific theories known as the semantic view of science. Van Fraassen, a well-known proponent of this theory, claims the work of scientists in practice concerns finding a best fit between theory and observations[18], which thereby displays 'empirical adequacy' (van Fraassen 1980). In a similar vein, Cartwright (1999) stresses the heuristic value of theories rather than their ability to correspond neatly with the very structure of the systems they are used to understand.

[18] As soon as scientific instruments such as simulations are involved, van Fraassen claims, observation in the strict sense is no longer possible: our ideas about observed objects partly rely on the functioning of technologies instrumental to the accessibility of these objects. In such cases, van Fraassen claims, one should speak of inferences rather than observations. See Giere (2006, 131-2) and Horsten et al. (2007, 103).

Simulations are not simply applications of theory. As Cartwright has argued, theories do not function as 'vending machines' in which simulationists can insert a problem and expect a model to pop out (Cartwright 1999, 179 ff.). Rather, simulations are composed of "a complex chain of inferences that serve to transform theoretical structures into specific concrete knowledge." (Winsberg 1999, 275) Modeling practice should be studied in situ, since it implies a process of exploration, framing and reframing of the issue at hand, and technical ability (Krohs 2008; Winsberg 2010). Morrison and Morgan (1999) propose to identify models as mediators, partially independent from theory and world (the target system). Theories provide the basic ingredients for model construction, after which a given model will function as an investigative tool:

> "It seems not quite correct to say that models accurately describe physical systems since in many cases they not only embody an element of idealization or abstraction, but frequently present the world in ways that bear no similarity to physically realizable objects […] Hence, we need a reformulation of the philosophical question; more specifically, since models are sometimes deliberately based on characterizations we know to be false how can they provide us with information about the world." (Morrison 1999, 38 quoted in Boumans 2004, 278)

Giere (2004) proposes to interpret the relationship between models and their target systems as a similarity relationship. Still, Küppers and Lenhard provide a warning why similarity between simulations and their target systems should not be taken too literally: in their view, simulations "do not provide numerical solutions" but rather "use generative mechanisms to imitate a dynamics ... Only simulation experiments allow to build models that imitate a dynamics without solving the relevant equations." (2005, 305, see also my previous remarks on 'discretization') The question is whether the simulation in question captures essential properties of its target system and correctly describes its underlying structure and dynamics, or simply reproduces the behavior of its target system without capturing any of the structural factors underlying the dynamics of that system.[19] In this sense, Küppers et al. (2006, 15) describe the former similarity as 'structural

[19] Numerical simulations may be physics-based (based on physical laws, e.g. classical mechanics), behavior-oriented (imitations of observed behavior of target systems), or data-driven (based on large amounts of data that may be processed using techniques related to data mining). Attempts to reproduce the behavior of target systems may be based on observation and measurement, and need not necessarily rely on data produced by means of (computer) simulations. I thank Huib de Vriend for pointing this out to me.

validity' and the latter as 'predictive validity'. Humphreys stresses the importance of the matter:

> "Because it is often possible to recapture observed structural patterns by using simple models that have nothing to do with the underlying reality, any inference from a successful representation of the observed structure to the underlying mechanisms is fraught with danger and can potentially lock us into a model that is, below the level of data, quite false." (Humphreys 2004, 134)

In short, the similarity between a simulation and its target system may be based on performance rather than accuracy, which means that prediction is not always tantamount to explanation. Beven stresses the importance of investigating 'equifinality': the idea that different models can provide "acceptable fits to observational data." (2006, 18) In other words, different models may produce output that fits observations of target systems although they arrive at this output in diverging ways. In such cases, model output matches the behavior of target systems, but whether the output of simulations and models is produced as a result of predictive or structural validity is the question.

In practice, acquiring structural validity can prove to be rather difficult. Model validation can be challenging (if not practically impossible) due to the stochastic nature of modeled phenomena, path dependency, the inability of the model to reproduce some aspects of the target system, incorrect assumptions and estimates underlying data collection, or the fact that simulationists are working with highly abstract models (Gilbert and Troitzsch 2005, 23-5). Knuutilla and Boon (2011) argue that an exclusive focus on the ability of simulations and models to represent is not very productive in terms of understanding how simulations and models figure in knowledge production. Instead, they propose to focus on how simulationists assess the value of simulations and models in practice. Simulationists may have confidence in their models when the latter correspond to well-established physical laws, when different models have corresponding outputs, when uncertainties are not (clearly) present, or when there is a good fit between observations and model output. In addition, simulationists will assess the value of simulations in the light of data and function:

> "Even if a perfect data match were possible in a model, simplicity, computability, or visualizability may, depending on the function of the model, tip the balance

towards a 'less perfect' model and the model user is the deciding factor in this." (Bailer-Jones 2003, 71)

Finally, institutional and organizational contexts may be highly important in the esteem models come to acquire in their contexts of application (Lahsen 2005; MacKenzie 2006; Sundberg 2006).

In light of the above, I propose to interpret simulations and models in terms of reliability and their use in practice rather than in representational or mimetic terms. Studies of the relationship between simulation and models and their target systems often tip towards the activities and concerns of simulationists, indicating that epistemological concerns also need to cover the terrain of simulation practice. What is more, as profoundly interesting as issues of representation are, they do not feature prominently in the field. Especially engineers are typically more concerned with finding pragmatic solutions to concrete issues. This is not to dismiss the importance of philosophical accounts of simulation and models and how they represent the world. Rather, representational work, empirical adequacy, and reliability suffice in raising issues concerning the relationship between simulation practice and vulnerability.[20] The heuristic value that simulationists attribute to simulations and models can be used to furnish a critique of simulation practice, as I will show in the following section.

2.3 Towards a critical account of simulation practice

As has become clear in the foregoing, simulation practice will inevitably involve some form of inscription as a result of abstraction and/or idealization. It is by virtue of distorting reality in some manner that simulations and models allow simulationists to study phenomena otherwise not accessible. If those phenomena were observable, there would be a less immediate need to construct simulations and models. Gilbert and Troitzsch identify this matter as a problem of weighing complexity and simplicity: "[t]he best map of the world is the world itself, but unfortunately such verisimilitude will tell us nothing about how the world works." (Gilbert & Troitzsch 2005, 20)[21] Simulations and

[20] I realize this will not please the reader interested in questions related to how simulations and models represent the world, who is hereby invited to study philosophical studies of simulations and models, e.g. Suárez 2003, Giere 2004, and van Fraassen 1980 and 2008.

[21] Borges' one-paragraph tale 'On Exactitude in Science' deals with the issue of balancing complexity and simplicity, and deserves to be quoted in full: "In that Empire, the craft of Cartography attained such Perfection that the Map of a Single province covered the space of an entire City, and the Map of the Empire itself an entire Province. In the course of Time, these Extensive maps were found somehow

models will always imply an approximation of actual systems or hypothetical states of those systems, are developed for a particular purpose, and will achieve credibility if they serve the work of simulationists in a manner deemed satisfactory. Thus, simulations and models do not have a straightforward relationship to truth and their target systems that can be captured by identifying their relationship with a presupposed and accessible real world.

Still, critiques of simulation practice are occasionally framed in terms of representation and mimesis. According to Turkle (2009), an important characteristic of modeling practices is that they feature an increasing degree of 'immersion', which can be defined more generally in terms of engrossing, enticing, or captivating influence of technologically mediated practices and experiences (e.g. Calleja 2011; Causey 2009). Turkle argues that scientific practitioners, designers, and engineers are increasingly wrapped up in modes of knowledge production that are infused with simulations, which makes it more and more unlikely that the work of scientific practitioners will escape the influence of these technologies. Immersed in modeling practices, simulationists straddle discovery and manipulation: "[s]imulation demands immersion and immersion makes it hard to doubt simulation. The more powerful our tools become, the harder it is to imagine the world without them." (Turkle 2009, 8) As a result, Turkle argues, a simulation may "propose itself as proxy for the real." (Ibid. p. 80) Rather than having an intimate relationship with models, a degree of mastery of their models, and persistent critical reflection upon the work carried out with these models, Turkle's simulationists increasingly take model output for granted. The 'transparency' attributed to older techniques like drawing (Ibid. p. 25) ensures a crucial "deep connection between hand and design" (Ibid. p. 16), which has been lost. Turkle assures the reader that maintaining this connection allows technological mediation to be 'lived' rather than accepted at face value.[22] Immersion implies that simulationists may be tempted to concern themselves exclusively with the surface of simulations, and are no longer concerned with how simulations present themselves as 'proxies for the real'. In the balancing act between

wanting, and so the College of Cartographers evolved a Map of the Empire that was of the same Scale as the Empire and that coincided with it point for point. Less attentive to the Study of Cartography, succeeding Generations came to judge a map of such Magnitude cumbersome, and, not without Irreverence, they abandoned it to the Rigors of sun and Rain. In the western Deserts, tattered Fragments of the Map are still to be found, sheltering an occasional Beast or beggar; in the whole Nation, no other relic is left of the Discipline of Geography." (Borges 1972)

[22] The work of Sennett (2008) also reflects on the consequences of severing the connection between mind and hand, and stresses the importance of mastery and virtuosity.

discovery and manipulation that simulation practice implies, simulationists appear to be tipping more and more towards manipulation, according to Turkle that is.

Turkle's work can be aligned with the work of Baudrillard (1994), where simulations are interpreted in terms of the concept of the 'simulacrum' – a deliberate distortion or copy that has a mere superficial likeness to some original. Baudrillard's concept of 'hyperreality' points to the ubiquity of simulations and their pervasive functioning in today's society:

> "Abstraction today is no longer that of the map, the double, the mirror or the concept. Simulation is no longer of a territory, a referential being or a substance. It is the generation by models of a real without origin or reality: a hyperreal." (Ibid. p. 2)

An underlying thread in the work of both Turkle and Baudrillard is that simulation implies some kind of 'covering up' of the world. Yet as I have shown above, simulations always imply some degree of inscription. In other words, all simulations can be critiqued in terms of a mismatch between 'simulated reality' and 'real reality', but this does not explain why truth, validity, and objectivity are attributed to simulations and models, or to what extent and how simulation practice puts technological cultures at risk.

According to STS scholars, the objectivity of science is not so much an explanation for the validity of knowledge, but needs to be explained itself by showing how various interests and scientific practices are intertwined. STS scholars inquire into processes whereby knowledge is produced by studying the various technological, institutional, economic, and socio-political aspects of knowledge production, and asking for whom a particular form of knowledge is important.[23] A long-standing tradition in STS, known as 'laboratory studies' (e.g. Latour & Woolgar 1986; Knorr Cetina 1999), starts from the observation that science does not provide neutral access to knowledge of

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[23] In Latour's work knowledge is seen a product of 'chains of translations', which is identified as "the work through which actors, modify, displace, and translate their various and contradictory interests." (Latour 1999, 311) As a result, knowledge can only be explained by a rigorous focus on practice, which reveals the various elements of chains of translation, or mediators, whose performances and persistence articulate knowledge. Note that this is not tantamount to relativism:

> "Science studies is not defined by the extension of social explanations to science, but by emphasis on the local, material, mundane sites where the sciences are practiced … [w]hat has been revealed through the study of practice is not used to debunk the claims of science, as in critical sociology, but to multiply the mediators that collectively produce the sciences." (Ibid. p. 309)

a world 'out there', but stages the conditions under which phenomena can be represented. Simulation practice can also be framed in terms of staging:

> "The art of simulating is that of the screenwriter: to put a *disparate* multiplicity of elements onstage; to define, in a mode which is that of a temporal, narrative 'if … then,' the way these elements act together; and then to follow the stories that are able to engender this narrative matrix." (Stengers 2000, 137, original emphasis)

The emphasis on knowledge *production* and staging rather than the acquisition of knowledge available 'out there' is not restricted to simulation practice, but applies to knowledge production across the board. STS can thereby draw attention to technological, institutional, economic, and socio-political aspects of scientific practices, and the commitments of social actors involved with these practices.

For example, Helmreich's study of modeling practice in research on traditional agricultural practices in Bali has shown that simulations have crucial mediating functions by virtue of explanatory value that is attributed to them: "[t]he computer simulation is designed as a didactic tool to connive otherwise skeptical engineers, bankers, and development officials that traditional cultural practices of agriculture are not only feasible, but exhibit a sort of 'evolutionary' – even 'natural' wisdom." (Helmreich 1999, 251) The problem with the simulation in question is that it glosses over political and economic aspects of the communities studied, and reduces these communities to an all-encompassing interpretation of nature as a system that seeks homeostasis. Simulations, Helmreich warns the reader, can "obscure these […] assumptions, hard-wiring them into the most basic parameters of a model." (Ibid. p. 250) In Helmreich's analysis, simulations cannot be seen apart from a "grid of power" (Ibid. p. 259), which implies that simulation practice needs to be understood against a broader context that contributes to the perceived truth of simulations.

The famous adage "all models are wrong, but some are useful" (Box & Draper 1987, 424) should be used with caution: arguing all models are wrong presupposes some objective measure against which their accuracy can be measured. In some sense, the model discussed by Helmreich is 'wrong', since it does not correspond neatly with a perceived reality. But in another sense, the model is 'right', since explanatory value is attributed to it, and it affects policy making in the context of agricultural development.

The perceived usefulness and reliability of models hint at pragmatic concerns of simulationists that occupy the center stage in this book.

Conclusion: beyond inscription and pathos

Although the staging implied in simulation practice will feature prominently in the following chapters, critiquing simulations and models *exclusively* in terms of staging is not very productive: simulation practice inevitably introduces simplifications in the forms of abstraction and idealization. Simulations and models are in that sense both enabling and constraining: they allow the production of knowledge in the form of proof, prediction, or explanation, but their output will always be influenced by their design that will inevitably involve inscription. This may render technological cultures vulnerable, for example because simulations and models are based on assumptions that turn out to have disadvantageous effects, or because they are seen as knowledge instruments that deliver exhaustive explanations without being subject to scrutiny or critical use. The goal of this book is not so much to lament the inscriptive aspects of simulation practice, but rather to propose various ways in which it can be studied on the basis of issues pertaining to construction, validation, and communication that emerge in simulation practice. A thorough study of the representational work of simulationists and the pragmatic concerns that pervade their work (developing a solution for the problem at hand), as well as the reliability attributed to simulations and models, can furnish a nuanced yet thorough analysis of simulation practice. Such an analysis can also indicate how simulations and models can put technological cultures at risk, without the need to rely on accusations of veiling 'reality'.[24]

In the following, I engage the various kinds of simulations and models used by simulationists and also study their reception in a broader context. As will become clear in

[24] This focus on simulation practice hints towards philosophical pragmatism, which provides an additional layer of meaning to the adjective 'pragmatic' from the title of this book. Wolfe characterizes pragmatism as follows: "first, in epistemological terms, its resolute antifoundationalist and antirepresentationalist stance, which eschews philosophy as a mode of 'transcendental inquiry'; and second, its relative instrumentalism and commitment to foregrounding the practical, material effects of thinking." (1998, xvi) What is more,

> "[p]ragmatism is also distinguished […] by its integrationist and contextualist rather than atomistic and analytical approach, one that holds that experience is rendered meaningful and coherent by organizing structures, patterns, gestalts, or language games that are themselves denied any foundational ontological status." (Ibid.)

Although this opens up linkages between the social constructivist framework deployed in this book and philosophical pragmatism, such a comparison warrants a more substantial discussion that is not of crucial importance to addressing the questions that occupy the central stage in this book.

the three case studies, simulationists often deploy a variety of simulations and models, which first of all implies I need to explain why certain models are deployed at particular stages of water management rather than others. Second, I look at various institutional aspect of simulation practice, in particular the various ways in which Deltares attempts to present its activities as innovative and cutting-edge, for example by contributing to new forms of governance and flood risk management. Third, I show how socio-political influences impinge on simulation practice. The present chapter provides a general explanation and outline of simulations and models and their epistemological aspects. However, social groups can (and often do) differ in terms of their demands and ideas pertaining to model construction, validation, and calibration, and the output of a given model. In addition, the particular form of simulations and models also shapes model construction, validation, calibration, and model output. For example, simulation practice can involve elaborate representations of water flow near coastal structures, but it may also take the form of a serious game. Both forms of simulation practice feature different methods of construction, validation, and calibration, and the output of these models most likely differs (e.g. 'raw data' in the former case, and an interactive and graphic appearance in the latter case). Despite these differences between kinds of models, the general characterization of simulations and models and their epistemological aspects that I discussed above can form the basis of a study of simulation practice. More generally, my approach to simulation practice can be aligned with 'thick descriptions' of technology that encompasses not only technological artifacts, but also knowledge and practices related to these artifacts, as well as their institutional, economic, and socio-political aspects (e.g. Pinch & Bijker 1984; Bijker 2010; Pinch 2010).

3. The craft of modeling: model construction in hydraulic engineering in The Netherlands since the early 20th century

Introduction

It takes Cees van Leeuwen (Head of Real Estate and Construction at Deltares) a while to unlock the doors, but eventually we enter the building housing the *Rijnmond* model – a tidal model of the waterways between the North Sea and the *Biesbosch* area, built on a scale of 1 to 65. After its completion in 1965, the *Rijnmond* model was used to study possible expansions of the *Rotterdam* harbor. When this research was completed, the model was used to study salinity intrusion. During the advent of computational modeling, the *Rijnmond* model was used to calibrate and validate the output of computer models. Over time the model became too expensive in comparison with computational models, which were becoming more and more reliable, and was eventually abandoned in the late 1980s. Upon hearing about the *Rijnmond* model and its imminent demolition, I felt fortunate to get an opportunity to pay a visit to this still tangible part of the history of hydraulic engineering in the Netherlands.

When we enter the building it becomes clear the *Rijnmond* model took a bit of a beating over the years. Windows and parts of the ceiling show signs of leakage, and patches of moss cover the floor and parts of the model. The lack of light inside the building makes me aware of the limitations of my camera. Luckily, van Leeuwen carries a flashlight, and repeatedly tells me to mind my step. Apart from a group of artists that organized an event in the building about 10 years ago, van Leeuwen does not think anyone visited the model since it was abandoned. Parts of the model, such as pumps and control panels, have been removed, as have a number of wooden beams from the roof that one employee of Deltares apparently used for 'personal purposes'. The basins for salt and fresh water used in model runs turn out to be intact, and are still filled to the brim, much to Van Leeuwen's surprise. The office complex adjacent to the model would not look bad in a publication on 'urban exploring'. We carefully avoid a number of large brown spots on the floor, and enter a room in the back of the complex. Van Leeuwen reminisces about a colleague who used to smoke cigars in this very office, where an empty chair now faces a window overlooking the premises of Deltares as a mute witness of things past.

The *Rijnmond* model was demolished in the summer of 2010. Although physical models are still used extensively by hydraulic engineers at Deltares, the latter have largely embraced computational methods. In this chapter, I look at how the experimental apparatus[25] of hydraulic engineering and the approach to modeling of various social actors have co-evolved. In other words, rather than looking exclusively at how simulations and models have developed over time due to technological innovations, I also align these technological changes with considerations of social actors, and maintain a thick description of hydraulic engineering. In the following, I take a closer look at the history of the construction and use of simulations and models in hydraulic engineering at Deltares and Delft Hydraulics. I study various forms of simulation practice from the early 20th century, which is when hydraulic engineers in the Netherlands started to use simulations and models.

The advent of information and communication technology (ICT) is often mentioned as a crucial factor in a supposed 'epistemic shift' towards computational models and computational science more generally (e.g. Agar 2006; see also section 2.1). However, as I indicated above, changes in simulation practice cannot be fully explained by looking at technological developments exclusively (such explanations would be replete with deterministic overtones, see section 1.2). Daston and Galison (1992 and 2007) have advanced similar concerns in a critique of 'instrumental determinism', the doctrine that studies of scientific instrumentation suffice in explaining changing ideals in scientific practice. The ideal of objectivity, Daston and Galison argue, takes shape according to 'epistemic virtues', which are "norms that are internalized and enforced by appeal to ethical values, as well as to pragmatic efficacy in securing knowledge." (Daston & Galison 2007, 40) Photography is often interpreted as a crucial technology that implied the advent of 'mechanical objectivity' – knowledge that represents the world 'as is' and is (supposedly) not 'polluted' by influences originating in scientific practitioners. The photographic method did play an important role in the establishment of mechanical objectivity, but only because ideas about what this form of objective knowledge entailed were already in place before the advent of photography. In other words, scientific instruments are important factors in effecting changes in epistemic virtues, but not the only source of such changes. Objectivity takes shape in a process of intertwining interests of scientific communities, technological developments, and socio-political strata.

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25 Agamben defines the term 'apparatus' not so much as individual technological artifacts, but in broader terms as "a set of practices, bodies of knowledge, measures, and institutions that aim to manage, govern, control, and orient – in a way that purports to be useful – the behaviors, gestures, and thoughts of human beings." (2009, 12)

Blackboxing and epistemic opacity

The foregoing description of technological developments and ideals of objectivity stresses the importance of thick descriptions of technological developments and their influence on various practices. In the following, I avoid instrumental determinism by developing a thick description of simulation practice in hydraulic engineering. I do so in order to study an important present-day characteristic of simulation and models in terms of their relationship to vulnerability: simulations and models are increasingly becoming 'blackboxed' (Latour 1987 and 1999). Blackboxing refers to

> "the way scientific and technical work is made invisible by its own success. When a machine runs efficiently, when a matter of fact is settled, one need focus only on its inputs and outputs and not on its internal complexity. Thus, paradoxically, the more science and technology succeed, the more opaque and obscure they become." (Latour 1999, 304)

Blackboxing may imply that simulationists are less likely to reflect on the design of simulations and models and the impact of the latter on their understanding of the world. This lack of reflexivity may imply immersion (see section 2.3). In the following, I engage the impact of blackboxing by means of Humphrey's notion of 'epistemic opacity', which he defines as follows:

> "The computational process leading from the abstract model underlying the simulation to the output […] is epistemically opaque relative to a cognitive agent X at time t just in case X does not know at t all of the epistemically relevant elements of the process. A process is essentially epistemically opaque to X if and only if it is impossible, given the nature of X, for X to know all of the epistemically relevant elements of the process." (Humphreys 2009a, 4)

Humphreys points out that agents may differ in terms of granting epistemic relevance to steps in the computational process underlying simulations and models. Humphreys' notion of epistemic opacity concerns both the instrument and its user since it influences the *ability* and *willingness* of a 'cognitive agent' to know details of the processes between input and output. Epistemic opacity may impinge on the ability and willingness of a user to "know that what the instruments display accurately represents a real entity." (Ibid.)

Thus, epistemic opacity can be seen as a characteristic of blackboxed technologies, in this case simulations and models: the latter's underlying complexity and everyday functioning according to expectations reduces the likelihood that social actors can or will question the simulations and models at their disposal, which can lead to immersion.

Humphreys observes that epistemic opacity could be interpreted as a departure from "individualist epistemology, within which a single scientist or mathematician can verify a procedure or a proof", to "social epistemology, within which the work has to be divided between groups of scientists or mathematicians, so that no one person understands all of the process." (Ibid. p. 5) However, Humphreys wishes to focus on different issues, and points out that "the sources of epistemic opacity in computational science are very different." (Ibid.) Humphreys claims the epistemic opacity of computer simulations implies that their relationship with the world cannot be fully comprehended by human agents.[26] The history of simulation practice in hydraulic engineering displays a shift from 'individualist' to 'social' epistemologies, and may contribute to epistemic opacity by dividing work related to simulations and models between an increasingly varied group of social actors. In this sense, I attribute more relevance to the shift from individualist to social epistemologies than Humphreys.

My empirical observations confirm that simulations and models are blackboxed technologies that feature epistemic opacity. As the earlier discussion of immersion revealed, simulation practice involves a balancing act between discovery and manipulation. In some cases, this balancing act may tip more towards manipulation as a result of epistemic opacity. However, it is questionable that simulationists automatically become subjected to the will of the wisp of blackboxed simulations and models. Hydraulic engineers at Deltares often display a critical attitude towards simulations and models, and adopt a 'craft-like' approach to modeling in which they carefully assess the impact of simulations and models on their understanding of hydrological and hydrodynamic phenomena. Despite these reflexive forms of simulation practice, the perceived reliability of simulations and models and the latter's codification in the form of

[26] Humphreys uses the concept of epistemic opacity to denote emergent features of simulation practice that reveals their inexorable prosthetic nature as knowledge instruments that cannot be fathomed entirely: running simulations generates emergent macro-level features that would not appear without the use of simulations. This requires new macro-level descriptions that will be able to capture these features. As will become clear later in this chapter and in section 6.2, my own argument confirms Humphreys' notion of epistemic opacity as a profound unknowability of simulations. I should point out these remarks cannot do justice to the depth of Humphreys' argument (e.g. the differentiation between equation-based and agent-based simulations), but I cordially invite interested readers to read his excellent work (e.g. Humphreys 2004; 2009a; 2009b).

computer software has widened the user base of simulation practice. Members of this broadened user base do not always share the craft-like approach to models adopted by the hydraulic engineers at Deltares.

Research questions and chapter overview

Adopting a thick description of simulation practice in hydraulic engineering avoids instrumental determinism, and shows how technological, institutional, and socio-political aspects of simulation practice have established simulations and models that feature epistemic opacity. The analysis of blackboxed simulations and models thus produced can be used to assess the danger of immersion. The main question of this chapter is then as follows: how has the experimental apparatus of hydraulic engineering changed over time in terms of epistemic opacity, and to what extent does the latter imply immersion? In section 3.1, I discuss the history of hydrological and hydrodynamic modeling in the Netherlands. I look at different forms of simulation practice, and describe how computational models became predominant in hydraulic engineering. In section 3.2 I look at how hydraulic engineers at Deltares have experienced changes in the experimental apparatus of simulation practice. Although these technological influences have indeed made simulations and models epistemically opaque, I also discuss how hydraulic engineers remain critical of their instruments and adopt a craft-like approach to modeling. In section 3.3, I show how simulations and models travel outside of their context of development in the form of software. I show how a broader audience of decision makers, policy makers, and stakeholders uses such software, and assess the effects of epistemic opacity that characterizes this software. The value of present-day forms of modeling is expressed in terms of openness and accessibility. I conclude the chapter by reflecting on openness and accessibility and whether present-day forms of modeling can alleviate the potentially harmful effects of epistemic opacity.

3.1 Formalization and scaling: a short history of simulation practice in hydraulic engineering

The corridors of the building of Deltares on the *Rotterdamseweg* are scattered with material traces of simulation practice. Old measuring equipment is displayed in glass cabinets. A model of a component of the *Oosterschelde* storm surge barrier that is part of the Delta Works stands in a forgotten corner. Elsewhere, a number of panels display photographs of physical models at Delft Hydraulics (section 1.3). The photographs display a certain intimacy between hydraulic engineers and their models, and show engineers standing knee-deep in water, for example to simulate different ways to close the final gap of dams under construction by means of caissons (watertight structures used to construct dams and bridges). The images indicate the material aspects of modeling (see figure 3.1), and depict the manual labor that accompanied model construction, such as the shaping of model components made out of soft stone by hand, digging trenches that would be used as model waterways, and coating molds with cement (see figure 3.2). I start taking pictures of the photographs in order to study them more carefully later, which was met with surprise and some mild enthusiasm by employees of Deltares who happened to walk by. One of them remarks "yes, that's history." During a later visit to Deltares, I noticed the panels had been removed from the hallway.

Inside the offices, only posters on the wall and titles of professional publications on bookshelves clearly point to the activities of Deltares. To the uninformed observer, the offices at Deltares may look like business as usual. By far most of the engineers work predominantly behind a computer, and some of them even use commonplace software like Microsoft Excel. Still, the location of the main building of Deltares on the *Rotterdamseweg*, the outskirts of *Delft*, provides a direct reminder of the erstwhile importance of physical models. When the building on the *Rotterdamseweg* opened in 1977, an important reason for choosing that particular location was that it provided much-needed space for experimental facilities. Today, the number of installations for physical modeling at Deltares is dwindling. Although the history of hydrological and hydrodynamic modeling at Delft Hydraulics shows that mathematical modeling and scale modeling co-existed for a long time, hydrological and hydrodynamic phenomena are now primarily studied by means of computational models. This transition towards computational modeling can be explained in very general terms as a matter of technological progress and increasing efficiency. On closer inspection, the advent of computational models reveals contestation, diverging opinions about modeling practice, and a gradual turn towards computational modeling rather than a sudden establishment thereof. An elaborate insight into this transition towards computational modeling helps to assess the influence of ICTs on the day-to-day activities of hydraulic engineers, which I discuss at greater length in section 3.2.

Figure 3.1 The *Rijnmond* model in operation. Note the devices used to register water levels located at various points of the model. © Deltares.

Figure 3.2 The Rijnmond model under construction. © Deltares.

Towards a mathematical approach in hydraulic engineering

Initial approaches to flooding in the Netherlands were defensive, and emphasized experiential knowledge rather than scientific theorization (Bijker 1996). The construction of waterworks resilient to the relentless attacks of floods, waves, and drifting ice were largely based on practical experiences, and much less on elaborate theoretical explanations of the phenomena in question. One of the earliest documentations of experiential knowledge is Andries Vierlingh's 1578 *Tractaet van Dyckagie*[27] (Vierlingh 1920). Regular measurement of water levels, commenced only in 1882, made it clear that the state of the coasts was worrisome in many locations. The behavior of water and sediment was then still largely unknown and attempts to understand these phenomena were usually unsuccessful.

From the early 20th century, hydraulic engineering can be characterized by a more thorough and systematic approach to hydrological and hydrodynamic phenomena, primarily due to large engineering projects that created a demand for such knowledge. In 1918, the Dutch parliament decided to commence the reclamation of the *Zuiderzee* (renamed to *IJsselmeer* after the completion of the *Zuiderzee* Works) after many decades of debating the matter. When Cornelis Lely (1854 – 1929) became minister of *Waterstaat* in 1913, he stressed the need for the reclamation of the *Zuiderzee*, which was met with general skepticism: too expensive, too many risks, and disastrous for fishery in the area. Lely managed to get the plan approved in 1918 after a severe flooding in 1916 and food shortages due to the First World War. The *Zuiderzee* Works would provide new land that could be used for agriculture, a reservoir of fresh water, increased safety from flooding, and reduced costs of dike maintenance. The most important and challenging feature of the *Zuiderzee* Works was the *Afsluitdijk*, a large dam in the *Zuiderzee*. The demand for knowledge related to hydraulic engineering increased, and brought about a burst of scientific activities in preparation of the construction of various waterworks. The increasing influence of physics and mathematics can be explained by the expectation that these disciplines would yield more elaborate and law-like theories that could be used in hydraulic engineering.

The construction of the *Afsluitdijk* meant its effects on the currents, tides, and water levels in the *Zuiderzee* (including the present *Waddenzee*) had to be predicted. Such changes would affect the required height of the dam, the dimensions of its sluices, and

[27] Though Vierlingh intended to record his experiences in five volumes, he passed away after completing the second volume of his treatise.

required the prediction of sand movements in the *Waddenzee* and determining the required increase in height of dikes in the area. Various opinions on the matter turned out to be a source of heated debate, in which the value of quantitative methods did not remain uncontested. Whereas Lely predicted a rise in water levels of mere centimeters in the immediate vicinity of the *Afsluitdijk*, an engineer by the name of de Bruijn predicted more dramatic rises in water levels, which meant that in some cases dikes in the area needed to be heightened by up to two meters. According to de Bruijn, quantitative methods did not suffice. Rather, "one has to feel it, as it were, based on experience gained elsewhere and on relevant research." (de Bruijn 1911) Lely was familiar with the struggles of political arenas, since he had spent many years persuading members of the parliament and the general public of the necessity of the *Zuiderzee* Works. Lely remarked that the study of the effects of the *Afsluitdijk* could never be a purely mathematical matter, but rather one of 'individual insight' (van den Ende & ten Horn-Van Nispen et al. 1994, quoted in Bosch and van der Ham 1998, 229). Lely installed the *Zuiderzee* Committee in 1919 and asked them to conduct a mathematical study of the effects of the *Afsluitdijk*. He chose to combine his own authority with that of the famous physicist Hendrik Antoon Lorentz (1853 – 1928), who won the Nobel Prize for physics in 1902. Upon being appointed as the head of the *Zuiderzee* Committee, Lorentz pointed out it was not common for a physicist to deal with such complex matters about which so little was known (Lorentz 1927). Lorentz called upon the assistance of the civil engineer J. Th. Thijsse (1893 – 1984), who was responsible for taking measurements that would aid in the construction of Lorentz' mathematical model. Thijsse would later become the first director of Delft Hydraulics. The commission took eight years to write its report, which was published in 1926 (Landsdrukkerij 1926).

Lorentz decided to use mathematical formulas from studies of fluid dynamics, which he simplified dramatically. Using these formulas, the *Zuiderzee* Committee performed calculations to describe the behavior of the *Zuiderzee*. Subsequently, the outcomes of these calculations were verified using data about tidal fluctuations, currents, and wind. Lorentz devised a schematization of the *Zuiderzee* that represented the gullies in the area as a system of canals. He then calibrated his model by comparing the results of the tidal calculations with the measurements of water levels and currents in he *Zuiderzee*, and used his method to predict the effects of the Afsluitdijk on tidal propagations, such as water levels during storm surges. The outcomes of the calculations eventually led to changes in the location and design of the *Afsluitdijk*, which were necessary to prevent harmful currents and flood hazards in surrounding areas. The method chosen by Lorentz involved a laborious trial and error process where two human calculators would perform necessary calculations in duplicate using calculating machines and slide rules, which remained a rather time-consuming process despite the use of simplified formulas. Lorentz concluded he had reached the limit of what could feasibly be achieved using a mathematical approach. Nevertheless, the predictions of tide patterns advanced by Lorentz turned out to be accurate within a margin of centimeters after the completion of the *Afsluitdijk* in 1933 (van den Boogaard et al. 2008, 52).

From 1930, the *Studiedienst voor de Zeearmen, Benedenrivieren en Kusten* (Research Service for Estuaries, Maritime Rivers, and Coasts, *Studiedienst* hereafter) was established by *Rijkswaterstaat* to study flood risks in the southwest of the Netherlands. History had shown this area was prone to disaster, and industrialization in combination with a growing population increased the demand for reachable harbors and a safe habitat. From 1934, the *Studiedienst* further improved the method of Lorentz under the supervision of J.J. Dronkers, and adapted the calculations to the conditions in the southwest of the Netherlands. Interactions between the tide and discharge of river water necessitated this process of adaptation, which made the process of doing calculations even more complex and laborious. The success of mathematical approaches to tidal movements eventually became detrimental to their application. Since mathematical calculations were used to determine the consequences of different plans, they needed to be accurate and provide reliable results. However, this meant the method became even more labor-intensive, especially since the number of alternative plans was also increasing.

The electrical analog method

In 1931, Johan van Veen, an employee of the *Studiedienst*, designed a simplified method to calculate tidal movements. Van Veen based his method on an 18th century theory that proposed an analogy between electrical currents and tidal currents (Voogd 2010). Representing the tidal currents by alternating electrical currents, van Veen argued, allowed the imitation of tidal currents. Van Veen lamented the lack of progress of the Lorentz method, and found its laborious character rather problematic. In 1937, van Veen warned that the Dutch dikes would be unable to withstand a storm surge, and that dealing with this matter would require more substantial calculations. Around that time fifteen employees of the *Studiedienst* were working on the Lorentz method under supervision of Dronkers. According to van Veen, the complexity of the calculations, the lack of qualified personnel, and the monotony of carrying out the calculations did not bode well for the success and applicability of the Lorentz method. However, the management of the *Studiedienst* considered van Veen's electrical method to be incomplete and unreliable due to its lack of validity, and continued to pursue their work along the lines of the Lorentz method. Despite the fact that van Veen and Dronkers were both part of the *Studiedienst*, they attacked each other's position vehemently. When van Veen continued to point out the timesaving effects of his method and its ability to quickly deliver predictions of flood-related risks, Dronkers retorted by showing that van Veen's approach would still require substantial preparatory calculations. In addition, even if time could be saved, Dronkers argued, van Veen's method still lacked completeness, validity, and reliability. Van Veen admitted that his method was less accurate than Dronkers' mathematical method, but continued to point out the importance of saving time. The debate between van Veen and Dronkers concerns two different approaches to hydraulic engineering. Whereas Dronkers was in favor of the accurate and labor-intensive method, van Veen emphasized the importance of faster methods, even if this implied less accuracy. According to van Veen, Dronkers' approach was labor-intensive and required relatively little but more experienced personnel. In contrast, van Veen's electrical method required more computing work with less experienced personnel (van Veen 1946).

Van Veen's position was dramatically supported by the events of February 1, 1953 (the flooding of the southwest of the Netherlands, see section 1.1), which led to a dramatic increase in resources allocated to hydraulic engineering. This affected mathematical approaches, electrical modeling, and scale modeling: all methods now faced an increased demand for elaborate hydraulic works, which featured increasingly complex technical challenges. After all, past successes had made hydraulic engineering and related research important aspects of political decision making. As a result, conflicts between the proponents of various approaches subsided, at least for the time being: "the way was cleared for less stringently valid, more approximate, but faster and more flexible styles of modeling." (Disco & van den Ende 2003, 535) Van Veen and Dronkers refrained from openly displaying their differences, and continued to pursue their diverging agendas. After the 1953 flood, the *Technisch Physische Dienst* (Technical Physical Service, TPD), a collaboration between the TUD and TNO, took over the development of the electrical method under the supervision of C.M. Verhagen. Together with Johan Schönfeld, an employee of Dronkers, van Veen completed the first analog computer in 1954. Due to the limitations of this first analog computer, construction of a second one began soon after and was completed in 1961.[28] These two analog computers were among the first of their kind in the Netherlands. The second analog computer later became known as Deltar (*Delta Getij Analogon Rekenmachine*, Delta Tide Analog Calculator, see figure 3.3), which was used to predict the effects of the Delta Works in the southwest of the Netherlands. In addition, the Deltar was used extensively to address questions related to coastal structures in *IJmuiden*, *Den Helder*, and *Scheveningen*.

Figure 3.3 The Deltar in 1972. Source: https://beeldbank.rws.nl, Rijkswaterstaat.

Eventually, the far more accurate and reliable method advocated by Dronkers prevailed, which was mainly due to the advent of digital computers that made it possible to perform the laborious calculations (Bosch and van der Ham 1998, 233). From 1963, Dronkers and his team used a digital computer for their calculations, the Elliott 503, though this did not yet mean the end for the Deltar. The mathematical approach had always been more accurate than the electrical method, but was much slower in comparison. Until the early 1970s, the Deltar remained superior to digital computers since it was considerably faster and easier to operate. The fact that electrical and computational methods coexisted for so long in this case also had to do with earlier

[28] There appears to be some disagreement on the exact date of completion. See Voogd 2010.

investments in the Deltar. The Deltar continued to be used until 1983 and was dismantled in 1984.

Scale modeling and the founding of Delft Hydraulics

During the rise of the mathematical approach developed by Lorentz and Dronkers, scale models became more established in hydraulic engineering.[29] Water works were becoming larger and more challenging, which made it even more important to prevent surprises and failures. In addition, alternative plans for water works were often proposed, necessitating a way to study multiple alternative designs. Scale models allowed hydraulic engineers to study the consequences of different waterworks by means of experiments, which also enabled a degree of control over the different conditions they would have to face in the field during construction. More generally, scale models "purported to bring the tiny, the huge, the past or the future within reach, to make fruitful analogies, to demonstrate theories, to look good on show." (Chadarevian & Hopwood 2004, 1) Scale models came with challenges of their own: large investments were needed for the construction and maintenance of scale models, and the experiments required substantial preparations in the form of measurements and calculations. Still, scale models provided more flexibility than the mathematical and electrical methods.

Although German hydraulic engineers started to use scale models at the end of the 19th century, scale modeling remained a somewhat exotic activity in the Netherlands until well into the 20th century. Early experiments were promising (e.g. Jolles 1909), but the Ministry of *Waterstaat en Onderwijs* (Water State and Education) requested research into the viability of a Dutch laboratory for research on hydrology and hydrodynamics as late as 1919. In that year, the *Zuiderzee* Committee used a model in The Hague to study the effects of floods and waves on the *Afsluitdijk*, and whether dikes were put at risk due to the *Zuiderzee* Works. As a result, scale models gained more trust among the members of the *Zuiderzee* Committee. With the assistance of Thijsse, German experts in Karlsruhe performed further experiments with scale models related to the *Afsluitdijk*. Combined with the mathematical approach discussed above, scale models contributed to improvements to the location and design of the *Afsluitdijk* and the process of its construction.

[29] Van den Ende 1992 suggests that this method was developed after the mathematical and electrical method, but this is not exactly true. Although scale modeling was adopted relatively late in the Netherlands, traces of it can already be found in the late 1910s and 1920s, see for example Jolles 1909.

Despite the dependence on German laboratories and the proven value of scale models, hydraulic engineers continued to question the usefulness and validity of scale models. Lorentz even opposed the use of scale models and doubted the relationship between scale models and their target systems could ever be explained exhaustively. More generally, physical models always imply issues related to scaling (Zwart 2009). The resulting scaling effects mean that the relationship between a scale model and its target system can be problematic. Scale models are developed with a particular question in mind, and should not be used outside of their intended application area. The *Rijnmond* model features an example of how engineers tried to deal with scaling effects. Small rotating elements were installed on the bottom of the model's rivers, which was supposed to imitate the effect of the rotation of the Earth on the flow of water (the so-called Coriolis effect). As I show in more detail in section 3.2, the effects of scaling continue to haunt the use of scale models in hydraulic engineering.

When additional experiments in *Karlsruhe* (Germany) supplemented the outcomes of the experiments conducted with the aforementioned scale model in The Hague, the critique of scale models subsided. Years of disagreement ensued among specialists at *Rijkswaterstaat* about the need for a Dutch laboratory for research on hydrology and hydrodynamics, and between governmental departments about who should be responsible for such an institute. In 1926, a trial laboratory was set up in *Delft*, which immediately proved to be of value. This led to the founding of Delft Hydraulics in 1927 with Thijsse as the director of the institute. Thijsse's experiences with Lorentz and the knowledge of scale modeling he acquired in Karlsruhe added to the influence of the institute, which soon proved to be of invaluable importance. In 1945, Delft Hydraulics provided assistance in the reclamation of *Walcheren* in the southwest of the Netherlands, which flooded after the retreating German army bombed dikes in the area. A technique using caissons was further improved using a scale model of parts of the delta in the southwest of the Netherlands built in 1946.[30]

The demand for ever-larger models plays an important role in the history of Delft Hydraulics. The institute occupied a basement of the TUD in 1927. A new location in the city center of *Delft* opened in 1932, but by 1965 proved too small as well, leading to the construction of the current main office on the *Rotterdamseweg* completed in 1977.

[30] Den Doolaard (2001) provides a detailed description of the use of caissons during the reclamation of *Walcheren*. Den Doolaard's book is reputed to have attracted numerous hydraulic engineers to their profession. Van de Ven (2004, 278ff.) further elaborates on the technical details of the use of caissons.

Large scale models were in popular demand after the Second World War. Especially after the famous flooding of 1953, physical modeling had become an even more prominent component of hydraulic engineering in the Netherlands. In 1951, Delft Hydraulics had already opened a laboratory in the *Voorst*, an open-air modeling facility of 120 hectares in the *Noordoostpolder*, which became a welcome location for experiments in the wake of the 1953 flooding. The location of the *Voorst* in the polder provided a supply of water under a head of four meters, which was convenient in terms of getting water to the various models. In addition, the availability of space for numerous scale models provided a basis for rapid growth. Finally, the soil at the *Voorst* laboratory is clayey, which prevents water from sinking into the ground and therefore makes the site appropriate for model construction. Large plastic sheets were occasionally used to prevent the weather from influencing experiments carried out in the open air. When more sensitive measuring devices became available, the management of Delft Hydraulics decided to construct several halls in the *Voorst* to create a more controlled environment for experimentation. The *Voorst* laboratory was abandoned in 1995. *Natuurmonumenten*, a Dutch foundation for nature conservation, now maintains the terrain of the laboratory. The *Deltagoot*, an installation used to generate waves, is still located in the *Voorst*. The installation's importance ensured it continued to be used extensively after the *Voorst* laboratory shut down, though its size also made it difficult to simply move the installation to a different location. However, now that the present *Deltagoot* is reaching the end of its life cycle, a new installation similar to the *Deltagoot* will be constructed on the premises of Deltares in *Delft*.

Although modeling techniques in hydraulic engineering have changed significantly, the shift towards computational modeling at Delft Hydraulics appears to be somewhat out of step with other disciplines (e.g. physics and meteorology), where digital computers were becoming more commonplace in the 1970s and 1980s. Periodicals and internally published reports of Delft Hydraulics from that era (Waterloopkundig Laboratorium 1976; 1977; 1978; 1979; 1987a; 1987b) indicate that scale modeling remained a highly visible part of hydraulic engineering at Delft Hydraulics at least until well into the 1980s. Aside from pictures of workshops and tables showing budgets related to the acquisition of sand, plaster, and wood, the aforementioned publications contain tentative musings and careful predictions of the advantages that computational models might entail. The possibilities of computer simulations were limited at this time, which often meant they were used in combination with other modeling techniques.

Another reason why scale models remained important for so long (and continue to do so) is their representative function. Since the founding of Delft Hydraulics, scale models had acquired currency as innovative and cutting-edge knowledge instruments. Visits to Delft Hydraulics by the Queen of the Netherlands, politicians, ambassadors, and heads of state, indicate the function of scale models as a display window of highly innovative Dutch hydraulic engineering. The representative function of scale models shows their importance as 'social technologies' as proposed by Shapin and Schaffer (1989, 25). As I show in chapter 4, present-day use of scale models in geotechnical engineering feature comparable representative functions.

Framing the epistemic shift towards computational modeling

Histories of hydraulic engineering often focus primarily on major historical figures, such as Lorentz, Thijse, Dronkers, and van Veen (e.g. Dirkzwager et al. 1977; van der Tuin 1998; Bosch and van der Ham 1998), all of whom were mentioned above. The advent of computational modeling is often mentioned as a matter of increased efficiency afforded by digital computers. This is certainly a substantial part of the history of computational modeling. The success of hydraulic engineering in the Netherlands led to increasingly challenging tasks, which was due to

> "the growing complexity of the hydraulic works and […] the enhanced role of tidal research in the decision-making process. The results were an increase in the number of alternative plans for which calculations had to be done and a demand for greater accuracy in the results." (van den Ende 1992, 32)

Eventually, computational models were able to meet these demands.

Before the widespread use of computational models, hydraulic engineering required the parallel use of mathematical techniques, electrical modeling and scale modeling. Digital computers could eventually replace these techniques to a large extent as a result of their reliability, accuracy, and flexibility. However, the gradual transition towards computational modeling should not be interpreted exclusively as a linear technological process implying more efficiency, since such an approach suggests that the increasing dominance of computational techniques can be explained without reference to social influences. Concerning the relatively late adoption of computational modeling in the Netherlands, van den Ende points out that computational modeling, or the 'digital approach',

> "was not a natural choice in the field of civil engineering, where most engineers had a preference for civil engineering methods … work was organized more like a *craft*, which tended to inhibit attempts to mechanize the calculations. This situation may well help to explain the lack of attention to the digital approach. It suggests that organizational factors were influential in the choice of digital computers." (Van den Ende, 1992, 32, my emphasis)

Rather than a sudden and neat shift from mathematical, electrical, and scale modeling to computational modeling, the history of hydraulic engineering suggests an intertwining of different methods, which only gradually led to the present-day dominance of computational modeling. In addition, these different approaches did not come about and develop in clearly demarcated historical episodes, but indicate a messy process of negotiation and contestation among various social actors. Mathematical modeling, electrical modeling, and scale modeling co-existed as supplementary and often competing methods. The gradual acceptance of computational modeling needs to be understood against the dominance of other forms of modeling, which only gradually gave way to novel approaches to hydraulic engineering. After all, these forms of modeling all proved their value in the period after the 1953 flood as less accurate yet faster and more flexible forms of modeling. Furthermore, the role of analog computers should not be underestimated. Although van Veen perhaps did not have the authority of Dronkers and Thijsse, the electrical method formed a crucial supplement to mathematical modeling and scale modeling. Especially in the 1960s, the Deltar filled the gap between the exact method of Lorentz and Dronkers, and the empirical method of engineers working at Delft Hydraulics (Voogd 2010).

More generally, the appeal of computational methods can be explained by a desire for quantified knowledge of hydrological and hydrodynamic phenomena that existed prior to the advent and widespread implementation of ICTs. The Dutch government has increasingly jettisoned its own research activities, which now need to be carried out by other parties. Marcel Stive, Scientific Director at the Water Research Centre Delft that is part of the TUD, recalls organizational changes at Delft Hydraulics during the 1970s and 1980s. Rather than focusing on fundamental research, Stive notes, hydraulic engineering was more and more pushed into the direction of applied research. Engineers working at Delft Hydraulics faced a decrease in the amount of time that could be devoted to fundamental research, and were expected to focus more and more on practical results. (Interview Marcel Stive, December 2, 2010) This demand for practical and tangible results is a broader trend that continues to exert its influence on hydraulic engineering. In this context, the transition from scale models to computational models also appears to meet a demand for tangible results in the form of quantitative knowledge, which is expected to enable a degree of control. As Latour points out, "[t]here is nothing you can dominate as easily as a flat surface." (Latour 1986, 19) Disco and van den Ende point out that computational models not only fulfill a crucial role in hydraulic engineering, but play a major role as management tools in Dutch water management as well (Disco & van den Ende 2003. The use of different modeling techniques and the gradual adoption of computational methods cannot be explained without reference to institutional and socio-political aspects of hydraulic engineering.[31] Omitting such aspects in analyses of the influence of technological innovations on modeling practice yields a deterministic view of the history of the experimental apparatus of hydraulic engineering.

3.2 Computational modeling and reflexivity

In this section, I further examine the advent and gradual establishment of computational modeling as the method of choice at Delft Hydraulics. I continue to frame the shift towards computational modeling engaged above by expanding my analysis to the day-to-day activities of hydraulic engineers. I study how technological innovations shape the activities of hydraulic engineers, and how the latter incorporate these technological innovations in simulation practice. This will explain not only how technological innovations relate to epistemic opacity, but also the ways in which hydraulic engineers deal with epistemic opacity. To that end, I study two technological innovations that are important in this respect: increases in computational power and developments in the area of measuring technologies.

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[31] After reviewing this chapter, Huib de Vriend pointed out that Delft Hydraulics failed to appreciate a number important opportunities, and as a result did not gain the upper hand in the development of computational models in the field of hydraulic engineering. For example, Delft Hydraulics rejected an invitation of Mike Abbot to contribute to the development of the so-called Mike series of the DHI Group, which has since become one of the largest competitors of Deltares. De Vriend also points out that the Dutch have yet to catch up with France and the United States when it comes to the possibilities of high-performance computing for hydraulic engineering. In sum, institutional and socio-political contexts cannot be ignored when discussing the history of Delft Hydraulics and its experimental apparatus.

Computational prowess

The adoption of computational modeling was influenced by increases in computational power, which allowed simulationists to model phenomena on high resolutions, work with large data sets, and perform multiple runs of a model. Research on turbulence and salinization carried out between 1986 and 1992 (Uittenbogaard et al. 1992), a time when computational models were gradually gaining foothold at Delft Hydraulics, illustrates how hydraulic engineers gradually embraced computational methods. Water movements near, for example, coastal structures can be characterized as turbulent due to the interactions between water and man-made structures. Turbulent water movements can also be found near coastlines. In such cases, the effects of water on coastal structures or coastlines may be difficult to predict, since the behavior of the water may contain little to no patterns, or that these patterns turn out to be remarkably difficult to find.[32] This means that for some studies of water movements, the use of scale models was (and remains) of crucial importance. Though the *Rijnmond* model was used to study the movement of water, salt intrusion, and transport of fine sediment in or near the *Rotterdam* harbor, its use and maintenance eventually became too costly. The transition towards computational models brought about a lack of expertise required to use the *Rijnmond* model (Ibid. p. 7).

The main reason computational models replaced scale models is that they formed a more flexible, efficient, and cheaper way to model hydrological and hydrodynamic phenomena, and not because they are epistemically superior to scale models (Siekmann 1998, 216 ff.). It is still undecided whether scale models can be fully replaced by computational models. Especially during the late 1980s and early 1990s, computer models were less suitable to study small-scale and fast currents that occur in highly turbulent areas, for example near coastal structures, which restricted the use of computational methods to the study of large-scale and slow currents (Uittenbogaard et al. 1992, 10). Small-scale phenomena still needed to be studied by means of scale models. The latter were also used to assess the ability of computational models to represent complex hydrodynamic phenomena using a simplified geometry (Ibid. p. 21). Physical modeling provides a starting point for the development of mathematical descriptions of

[32] Daston and Galison (2007) discuss present-day examples of research on hydrodynamic phenomena, which are studied by means of computational approaches and more 'artistic' representations where aesthetic appeal and scientific erudition appear to be intertwined. See for example the work of van Dyke (1982) and Samimy et al. (2003), whose work is also discussed in the work of Daston and Galison (2007, 402ff.).

hydrological and hydrodynamic phenomena (Ibid. p. 11). Scaling effects notwithstanding, the advantage of scale models is that they bear a physical resemblance to the phenomena they are meant to simulate. When using computational models, hydraulic engineers need to make sure all of the relevant processes are captured or described by the equations underlying the model.[33] Failing to incorporate these processes into the model will result in systematic errors and nonsensical results. In sum, scale models provided a crucial starting point for computational methods, and were used for the purpose of validating and calibrating computational models.

Uittenbogaard et al. (1992) describe how hydraulic engineers carefully assess the ability of computational models to provide mathematical descriptions of phenomena that were previously studied by means of scale models. The activities of hydraulic engineers also display pragmatic considerations pertaining to the level of detail required for a particular task. The extent to which computational techniques suffice is investigated by means of an elaborate process of finding the right tool for the job at hand: "hydraulic engineering remains a craft, especially where science lacks knowledge and/or tools." (Ibid. p. 6) During the transition from physical models to computational models, hydraulic engineers working on turbulence and sediment transportation deployed different modeling techniques as exploratory devices, where different modeling techniques were valued on the basis of their ability to generate relevant and sufficiently detailed insights. This example shows that hydraulic engineering proceeded in a craft-like fashion, as is suggested by van den Ende (1992, 32; see previous section). These references to craft and the use of models as exploratory devices describe an attitude towards simulations and models that can also be found in present-day forms of simulation practice.

As the ongoing extensive use of physical models in hydraulic engineering shows, computational models have not completely replaced scale models in studies of complex turbulent flows, e.g. near coastal structures. Hydraulic engineers consider computational models sufficiently adequate to describe large-scale phenomena, which decreased the demand for costly and labor-intensive scale models that replicate large-scale water systems. Large-scale water movements can be modeled computationally. If necessary, physical models can provide a supplement to such models in order to understand the behavior of water, e.g. near the coast and/or coastal structures. As a result, the use of

[33] Capturing these phenomena would be tantamount to structural validity. Successfully describing the behavior of the system in question would imply predictive validity. See section 2.2.

scale models is pushed more and more into the fringes of hydraulic engineering as the means to study small-scale hydrodynamic phenomena, such as the interactions between water movements and coastal structures. Marcel Stive stresses that advanced computational models require detailed calibration and validation by means of physical models, making the latter far from obsolete. (Interview Marcel Stive, December 2, 2010) According to Huib de Vriend, Science Director of Deltares, it is necessary to assess the impact of simplifications that accompany the use of simulations and models. A modeler should never rely exclusively on one particular method and should strive for a diverse approach. Sadly, de Vriend remarks, this critical attitude towards modeling is sometimes missing in hydraulic engineering. (Interview Huib de Vriend, March 5, 2009)

Marcel van Gent, head of the Coastal Structures department at Deltares, stresses the importance of scale models in terms of accuracy and detail. Van Gent's department makes extensive use of computational models, e.g. to model the impact of waves on coastal structures. Increases in computational power have improved computational models in terms of accuracy and speed, which has increased the number of areas where computational models can be used successfully. However, van Gent stresses the complexity characteristic of hydraulic engineering. Coastal structures respond to water in various ways: the flow of water may induce vibrations in coastal structures, or may move rocks used in flood barriers. Studying such phenomena requires empirical knowledge that can only be provided by scale models. When such knowledge needs to be included in computational models, hydraulic engineers need to have a substantial understanding of the interaction between water and coastal structures. Computational models that fail to describe these interactions can put coastal structures at risk. For this reason, physical models continue to provide crucial means to validate and calibrate computational models. Van Gent points out that the previous trend to abstain from using scale models is now even reversing due to an increasing demand for more accurate knowledge about the behavior of coastal structures. Scale models of coastal structures play a role of great importance in optimizing their design, which reduces the costs of maintenance and construction.

Still, van Gent experiences difficulties in pointing out the importance of scale modeling. Civil engineering students sometimes think everything can be modeled by means of computer simulations, which is a concern voiced by Marcel Stive as well. Policy makers and decision makers sometimes think a computational approach suffices, which in van Gent's experiences also relates to previous successful applications of computational models. Calculation rules may have a solid and convincing appearance to certain social actors, which may veil underlying disagreements between experts. Whereas the validation of models can be the source of heated debate among experts, policy makers or decision makers may think a calculation rule is reliable simply because an expert judgment on the matter has been produced. A further complication is that scale modeling is a costly form of modeling. Van Gent does point out this is a matter of perspective. Although the potential savings are far greater than the costs of experiments that deploy scale models, van Gent experiences difficulties convincing contractors of the potential value of scale models, especially against the perceived reliability of computational models. Finally, the expertise required for scale modeling is becoming scarce, which exerts more stress on an already marginal form of modeling. (Interview Marcel van Gent, June 4th, 2009)

More generally, hydraulic engineers at Deltares critically approach increases in computational power, and do not automatically embrace computational prowess as a premonition of more advanced and elaborate forms of modeling. Van Gent: "you just look for the right tools on a case by case basis." (Interview Marcel van Gent, June 4, 2009) The tendency of hydraulic engineers to look for the right tool for the job at hand also becomes apparent in their ideas about model resolution. Although increases in computational power have allowed hydraulic engineers to model phenomena in higher resolutions, this potential is not always realized in practice for two reasons. First of all, models have a degree of obduracy that precludes hydraulic engineers from tapping into the potential of increased computational power. Models may be developed for a particular purpose and may deliberately represent a target system in a simplified manner. Making sure the model performs equally well on a higher resolution may require a different approach. In addition, models may contain lines of code that cannot simply be omitted or modified to new possibilities afforded by increases in computational power. For example, a model may contain parts of Fortran[34] code, which are usually left alone without being subject to thorough evaluation due to a lack of time and expertise. The number of hydraulic engineers that are able to deal with Fortran code is decreasing as well. Various hydraulic engineers have explained to me how old code can be hard to understand, which sometimes forces them to rely on work carried out many years ago. These model components may or may not have a severe impact on simulation practice.

[34] A programming language that was first developed in the 1950s and became prominent in scientific computing in areas such as fluid dynamics and meteorology.

A second reason why hydraulic engineers do not always tap into the possibilities afforded by increases in computational power concerns pragmatic considerations pertaining to model performance and accuracy. Jaco Stout of Deltares points out that hydraulic engineers will often try to push the envelope. If increases in computational power allow more detailed calculations and more model runs, hydraulic engineers will attempt to make their models more detailed, provided it does not take too long for a model to produce its output. (Interview Jaco Stout, June 19, 2009) In hydraulic engineering, long calculation times are not only unacceptable due to limits of time and resources, but also because hydraulic engineers will want to have the ability to do multiple model runs. Input values typically have a great effect on the output of a model, which is why hydraulic engineers consider studying the effects of different input values of great importance. For example, they may want to calibrate models by using different input values, and make adjustments in the model's code or schematization where necessary. Gerben de Boer, Senior Researcher at Deltares, explains that the ability to do multiple model runs is also a matter of keeping the model "under control". (Interview Gerben de Boer, June 19, 2009) De Boer mentions three rules of thumb for keeping calculation times in check: model runs should take either five minutes (the time it takes to get a cup of coffee), one night (so you can check the results in the morning), or two days to a week (so you can run the simulation on Friday and check the results after the weekend or after a holiday). De Boer refers to calculations that take longer than a week as

> "'count your blessings' calculations … it is interesting to see what comes out of it, but you cannot rely on it … a model can perform calculations, but you have to understand what is happening … you have to know what you are looking for, so you have to understand the underlying physics. The model cannot replace your insights that are based on physics." (Interview Gerben de Boer, June 19, 2009)

More complex calculations have certainly become more accessible to hydraulic engineers. During the early days of computational modeling, one often had to file a request for a particular calculation at a designated department of one's institution or company, and then wait for the results for one or several days. The slightest mistake in the schematization or calculations underlying a given model would result in model output that could not be used. Adri Verwey, Senior Specialist Modeling Systems at Deltares, who has worked on a variety of hydrological and hydrodynamic models since the 1970s, points to the importance of his expertise regarding the computational abilities of early computer simulations. During his student years, Verwey was doing research on the only mainframe available to him at the time. Verwey admits the concentration and attention to detail could be a nuisance. But he also points out this made him think very carefully about the way the model was set up, and made him pay attention to the limitations of the model. When he was able to use the mainframe for an extended amount of time on a quiet Sunday, Verwey noticed that he was "just doing some calculations" and was not really paying the attention normally required to ensure the quality of the model's output. (Interview Adri Verwey, May 27, 2009)

Although mathematical and computational progress have certainly played an important role in the perceived success of computational models, many engineers argue that models needs to be approached critically by aligning them with their experience. Increases in computational power allow simulationists to develop models that are more elaborate, or perhaps perform multiple model runs to model a variety of scenarios. However, increases in computational power do not necessarily lead to an enhanced understanding of target systems. When they do not understand the target system, base the model on ill-founded assumptions, or fail to comprehend the intricacies of a given model's design, the hydraulic engineers at Deltares fear they end up using premature models that they do not really understand or approach critically.

Measuring devices

Innovations in the realm of measuring technologies have led to more reliable and less disruptive measuring devices. These new means of measurement have improved the accuracy and reliability of measurements in experiments with scale models in laboratories. In addition, new measuring technologies contribute to the calibration and validation of high-resolution computer simulations. As argued above, increases in computational power have enabled hydraulic engineers to develop more elaborate computer simulations, which increased the demand for highly detailed measurement data. At Deltares, even hydraulic engineers who work primarily or exclusively with computational models will readily admit that simulation practice necessitates elaborate measurements, since similarities between a given model and target systems may be coincidental. However, present-day developments in the realm of measurement technologies (e.g. satellite monitoring, sensor technology, Laser Imaging Detection And

Ranging or LIDAR, and the sharing of data between institutions, for example via the Internet) can imply diminished attention to modeling and more focus on observation and data collection. Observation- and data-driven approaches to water-related risks allow model construction and validation on the basis of measurement data, which is more and more often shared among the parties involved.

Apart from using measurements for the purpose of validation and calibration, it is also possible to do 'hindcasting'. In the latter case, a model's ability to predict an event that already occurred is compared with measurements or observational knowledge related to that event. The advantage of hindcasting over forecasting is the possibility that more data about the event is available, which can be used to judge whether the model in question is able to predict such events. From the perspective of the model, so to speak, it does not matter if you predict the 'real' past or future of a target system: for the model, both events are future states of affairs.

Simulation practice also differs from measurement and observation in important ways. The various ways in which hydraulic engineers use measurement data displays pragmatic considerations that emerge in their day-to-day activities. Such considerations are comparable to how hydraulic engineers approach increases in computational power, as described above. One advantage of simulation practice is that it allows simulationists to avoid the tedium of measuring phenomena in the field. In addition, simulations and models can be used to exaggerate conditions found in the field. Extreme conditions that have a low probability in the field can be generated on demand in a laboratory. Thus, simulation practice may involve 'misrepresentations' in those cases where conditions in the field are deliberately exaggerated. Van Gent stresses the shortcomings of these experiments (e.g. scaling effects that need to be taken into account), but measurements in the field have limitations of their own:

> "Say you're talking about wave conditions that occur once every 10,000 years … this will make your measurements obsolete because these conditions will never occur in the field … that is the risk of setting up a measuring campaign in the field, once you put down your instruments, the storms will not occur anymore (laughs)." (Interview Marcel van Gent, June 4, 2009)

Due to the shortcomings of modeling and measurements, van Gent advocates combining these approaches when necessary.

Despite their inscriptive aspects, simulations and models provide an opportunity for hydraulic engineers to ask questions about states of affairs that may never be witnessed. Simulation practice helps to overcome some of the limitations of measurements, where the inevitability of human error and the snapshot-like character of taking measurements can inhibit the possibilities of hydraulic engineering:

> "The use of models will never allow you to predict phenomena with complete certainty, but the nice thing about models is that they yield a consistent image in relation to measurements and how they were used in the past … in order to say something about a system, measurements were made on one location and on another, but there was no *consistency*, right? So when an error would occur in doing the measurements that would be hard to detect. This may be a bit of a simplistic image, since there are other processes that will make [modeling] even more complex, but at least … you will have the *consistency* of the model." (Interview Adri Verwey, May 27, 2009, emphasis added)

This consistency, Verwey argues, allows him to identify measuring errors and discuss his work with his contractors. Talking about the model and presenting model output has the ability to provide "an interesting discussion." (Interview Adri Verwey, May 27, 2009)

Hydraulic engineering and epistemic opacity

The various ways in which hydraulic engineers at Deltares deal with technological innovations display a persistent critical attitude towards the ability of models to represent reality. Frequently encountered statements like 'it is only a model' or 'it is just a tool' illustrates their perspective regarding the explanatory potential of models quite well. According to Guus Stelling, an applied mathematician involved with software development at Deltares, models cannot prove anything, but can only show you the consequences of your own assumptions. Stelling's characterization of modeling practices helps to understand the critical approach to models characteristic of hydraulic engineers at Deltares. This critical approach can be further illustrated by discussing the question-driven character of models, the persistent refusal of hydraulic engineers to take simulations and models literally, and the importance they attribute to being familiar with a given model's inner workings.

According to hydraulic engineers at Deltares, any model is first and foremost a simplification of reality developed with a certain purpose in mind. As a simplification of a more complex system or phenomena, a given model may generate useful insights. Models are in this sense question-driven, meaning that an engineer needs to know what he or she wants to find out when constructing a model. As Edward Melger, Product Manager at Deltares, explains:

> "You only construct a model once you have a question you want to answer … if the question is not clear, you can have a very nice model that delivers a beautiful answer, but it can never be correct. The question first needs to be clear." (Interview Edward Melger, May 26, 2009)

As Marcel Stive pointed out, "the model does not tell you how things work, but should only conform whether things work in the way you thought they did beforehand." (Interview Marcel Stive, December 2, 2010) Gerben de Boer argues that the output of a numerical model is merely an advanced version of a 'back of the envelope' version of a target system (a rough schematization and characterization of a target system based on expertise). The model can only provide more detail, not a radically different answer or a profoundly deeper understanding of phenomena: "if you do not know, roughly, what comes out of it beforehand, you do not need to run a model. I would say a numerical model is nothing more than a refinement of something you can do yourself." (Interview Gerben de Boer, June 19, 2009) In case of more exploratory use or a mismatch between a modeler's own ideas and model output, a numerical model functions more like what de Boer refers to as a 'sparring partner' in the sense that a model might challenge your own thinking and lead to new insights:

> "A model should match the goal. If you do not know what you want, the model is wrong in any case. You have to know what your question is beforehand, so if you do not know what your question is, the model is more like a sparring partner that might be able to tell you something about the system." (Interview Gerben de Boer, June 19, 2009)

However, as de Boer points out, a model "might tell you the wrong things about the system because it has been constructed for a different purpose." (Interview Gerben de Boer, June 19, 2009) Sometimes a modeler needs to take a step back and see whether a model can indeed be used to answer a particular question. For example, a two-dimensional model of a lake can be used to model water levels, but not for modeling sediment transport since such events involve three-dimensional processes where different layers of water interact in turbulent processes. Successful applications of a model in one problem area by no means guarantee for similar successes in another problem areas. Understanding the model's design is therefore necessary to assess whether it can be used to address a particular question. Simulationists should therefore gain familiarity with the model they are using in order to understand the implications of its use, for example by studying the questions that informed the construction of a particular model, how the model is constructed, how the model's schematization relates to its target system, and what data is used as input for the model in question.

Understanding these aspects of a model enables the modeler to have a degree of control over his or her instruments, which hydraulic engineers at Deltares see as a necessary precondition to any elaborate form of simulation practice. Verwey argues hydraulic engineers should develop their expertise by critically reflecting on the simulations and models they are using. Verwey admits his own career puts him in a rather fortunate position in this respect, since he experienced the very early stages of model development. This provided him with knowledge of fundamental design principles, which he still considers to be a crucial component of his expertise. (Interview Adri Verwey, May 27, 2009) The present-day generation of hydraulic engineers often simply does not have the ability to study the design of simulations and models in such detail, and is in that sense often condemned to using simulations and models 'out of the box'. Some modelers I encountered at Deltares have spent years, sometimes decades working on a particular model. Some jokingly remark they have seen every line of code countless times, and that the model literally has become a part of their lives. Although different generations of modelers may have different degrees of familiarity with a model's design, it is certainly not the case that younger generations of modelers are no longer interested in understanding the deep-seated design of their models, especially since understanding a model's design is still considered 'good modeling practice'.[35]

[35] Turkle (2009) elaborates on the uncritical adoption of simulations by younger generations. However, who these users are, why they act in the various ways they do, and what simulations and models they have at their disposal remains unclear. As a result, Turkle's discussion of present-day generations of simulationists displays an unnecessary amount of pessimism, perhaps even resentment.

Still, characteristics of present-day simulation practice do not bode well for commitments to fully grasp the design of simulations and models and the implications of their use. Simulations and models are more often developed and maintained by groups of people rather than individuals. What is more, software developers more and more often carry out the development and maintenance of simulations and models, distributing simulation practice over an even larger and more varied group of social actors. Over time, simulation practice has also become firmly intertwined with policy making, as was discussed in the previous section. The perceived reliability of simulations and models due to successful applications in the past has also increased the complexity of challenges they are expected to address. As a result, more intricate and elaborate simulations and models need to be developed. In sum, the dispersion of simulation practice over a larger and more varied group of social actors and the fact that simulation practice faces increasingly complex challenges appear to exacerbate epistemic opacity.[36]

According to de Boer, simulations and models are indeed becoming more opaque, which makes it all the more important for simulationists to be in control: "once you do not have the model entirely under control, you are actually already in a danger zone and you cannot use it to make predictions since you have no idea what is happening." (Interview Gerben de Boer, June 19, 2009) Model output will always provide some answer, these days more and more often an aesthetically appealing one, so the importance of understanding how the model arrived at its output appears to be increasing. De Boer argues simulationists should never trust simulations and models 'out of the box'. It is far better to become familiar with the model in an exploratory manner, e.g. by starting with relatively simple phenomena, such as the discharge of a larger river. Other aspects of the river can then be added incrementally, leading to the study of more and more complex phenomena. According to hydraulic engineers at Deltares, accepting the model's design and using it immediately to address highly detailed and complex issues is unacceptable and tantamount to 'irresponsible' use of models. Simulation practice requires that simulationists dedicate themselves to becoming familiar with a given model, and use it to gradually tease out potentially relevant and applicable insights to more and more complex issues.

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[36] It should also be noted that there are often multiple models or modeling packages suitable for studying the very same issues. These models or modeling packages each have their own history of development and underlying design. Although the fundamental principles on which modeling software is developed can be similar, becoming familiar with the design of this software in practice may require substantial effort on the part of simulationists.

Progressing understanding

As much as hydraulic engineers at Deltares adopt a critical attitude to simulation practice, their work also features pragmatic considerations, some of which already surfaced above. Increases in computational power and improvements in the realm of measurement cannot be translated to the practice of hydraulic engineering in a straightforward manner. Rather, these innovations are approached critically on the basis of the expertise of hydraulic engineers, and are subsequently translated to meet the specificities of the task at hand. In some cases, the use of highly simplified representations of target systems can be justified when they capture all of the physical processes that are considered to be relevant. This points back to van Veen's defense of the electrical method: emphasizing speed over accuracy might be justified in some cases. Similarly, hydraulic engineers assess the value of technological innovations in terms of *sufficiency*, not *accuracy*. As Karel Heynert, Head of the Hydrodynamics and Operational Systems Group at Deltares, points out somewhat ironically, his work is about finding solutions for problems, and not vice versa. (Interview Karel Heynert, June 10, 2009) The importance attributed to being familiar with a model's design show how hydraulic engineers attempt to find the right tool for the job at hand, whilst making sure they use that tool responsibly at the same time.

These contextual and pragmatic considerations notwithstanding, hydraulic engineers do appear to believe computational models are becoming more successful in terms of understanding and predicting hydrological and hydrodynamic phenomena. The hydraulic engineers at Deltares often refer to this as 'progressing insight', which might appear to contradict their critical attitude towards models. However, the reliability of simulations and models is not so much explained in terms of their ability to yield an objective understanding of the world, but rather in terms of heuristic currency based on practical results in the past. The hydraulic engineers at Deltares continue to adopt a critical attitude in simulation practice, but also value strong correlations between model output and measurements as proof they can trust the model in question. The history of Delft Hydraulics and its many successes, which were to a major extent based on simulation practice, are frequently mentioned as a source of this trust.

However, hydraulic engineers at Deltares still abstain from stipulating future successes of simulations and models. For example, van Gent points out that it is difficult to make hard claims about the progress or reliability of simulations models, since the issues they are meant to address and their application area co-evolve with societal demands. (Interview Marcel van Gent, June 4, 2009) In a similar vein, Edward Melger admitted that models can be applied successfully in the study of certain issues, but understands their value in terms of the insights models can provide to simulationists. Melger also does not think models are approximating reality more and more since they are never completely exhaustive. Rather, simulation practice consists of balancing the questions models are supposed to address against the model's possibilities and measurement data that happens to be available. (Interview Edward Melger, May 26, 2009)

Hydraulic engineers at Deltares stress the provisional character of their work, and persistently evaluate the ability of simulations and models to provide access to fundamental principles or law-like structures of reality. According to Simone van Schijndel, Manager of Operational Water Management group at Deltares,

> "it is not so much the case we are not interested in that, but rather that we realize it is not possible, and that is where I think there is a discrepancy with the policymaker, who I think does consider it to be possible … we are well aware of the fact that is just not reality, which is out there, not here in the computer." (Interview Simone van Schijndel, June 24, 2009)

Since most policy makers demand clear-cut answers, van Schijndel had to withstand a lot of critique when she wrote reports that stressed the need for more research in order to deal with uncertainties.[37] For her, modeling is much more about making abstractions to a particular end and not about approximating reality as well as possible. Even measuring what happens in reality is problematic since the behavior of real systems often contains noise, e.g. passing ships, storms, etc. "So you have to construct a model. At the same time it is very crucial that your models describes accurately what happens … so in that sense you arrive in a paradox, or a deadlock, what is reality?" (Interview Simone van Schijndel, June 24, 2009) To sum up, hydraulic engineers at Deltares may speak of the reliability of simulations and models in terms of progressing understanding. However, this claim is based on practical results, and does not diminish their reflexive and critical approach to simulation practice.

[37] Although the call for more research can be justified, it is also likely that additional research will not be able to (completely) eliminate uncertainties. Rather, uncertainty can be approached as a potential source of knowledge, as I argue in chapter 4 and section 6.3.

Craft in an age of codification

Although hydraulic engineers at Deltares deliberately simplify target systems in order to produce practical solutions for concrete problems, they also engage simulation and model in a critical and reflexive fashion. Hydraulic engineering at Deltares in that sense features a craft-like approach to simulation practice. Craft can be understood as “the application of skill and material-based knowledge to relatively small-scale production”, or in more general terms as “a set of concerns that is implicated across many sites of cultural production.” (Adamson 2010, 2-3) A myriad of activities display the ideal of craft, such as the production of artisanal cheeses and architecture, which oppose the mechanization associated with industrialization and Taylors mass production. Ingold (2010) extends the notion of craft to various forms of product-making (e.g. carpentry) and artistic practice. He claims craft-like practices should not be explained as a relationship between human agents and inert matter, where the former shape the latter according to a preconceived idea of what they desire to produce.[38] Instead, Ingold argues that ‘making’ involves “not so much imposing a form on matter as bringing together diverse materials and combining or redirecting their flow in the anticipation of what might emerge.” (Ingold 2010, 94) Making should be understood as a process of artisanal production involving interactions between form and matter, where human agents pay careful attention to the properties and affordances of matter they are dealing with in the production process. Similarly, hydraulic engineers at Deltares do not tame target systems by projecting rigid forms onto them in simulation practice, but use simulations and models in an attempt to generate insights. This critical and reflexive use of simulations and models entails a process of ‘teasing out’ knowledge rather than imposing some rigid structure of a model onto a given target system.

Nonetheless, hydraulic engineering is not a free-floating activity that is exempt from institutional and socio-political influences. As became apparent above, the perceived reliability of computational models has increased across the board: not only in the eyes of policy makers, but also for hydraulic engineers. Modeling and simulating phenomena in hydraulic engineering are increasingly framed as computational tasks, as I

[38] The opposition between form, imposed by a human agent, and inert matter is known as ‘hylomorphism’, which was first developed by Aristotle. Simondon (1992) criticizes hylomorphism by questioning the binary opposition between form and matter. For example, brick making cannot be explained as a process of imposing a form (mold) on inert matter (clay). Rather, clay contains self-organizing properties that enable the production of bricks as the outcome of the interaction between clay, molds, brick makers, and brick ovens. Although Ingold refers to hylomorphism, his paper does not refer to the work of Simondon, which is remarkable given the latter’s work on hylomorphism and growing popularity in present-day philosophy.

showed in the previous section. The establishment of computational modeling as the method of choice in hydraulic engineering has led to an increase in codification: the act of systematization whereby knowledge is accumulated and organized into a system, for example modeling software that is maintained, distributed, and supported by Deltares. Codification replaces tacit knowledge by explicit articulations of knowledge, and subsumes the work of a highly skilled work force by automated processes that have greater efficiency and can be run at a lower cost. Automation attempts to replicate the performance of this highly skilled work force, but the latter's tacit ability to deal with unforeseen circumstances and innovate may be lost in the process of codification (Lam 2000). As the previous discussion has shown, technological innovations are not automatically adopted as sources of previously unforeseen possibilities, at least not by the hydraulic engineers at Deltares. It is questionable whether computational prowess and new measuring technologies can replace the hydraulic engineer, at least at the present time: simulations and models cannot be applied out of the box, and need to be adapted to the specificities of target systems. As a result of codification, simulation practice becomes black boxed in the form of modeling software, which can travel outside of its context of development to contexts of use where simulationists and other social actors may not be committed to the aforementioned craft-like approach to simulation practice.

Such social actors feature a lesser degree of 'inclusion' (Bijker 1987), meaning they work outside of the 'technological frame' (Bijker 1987; 1995a) in which simulations and models are developed. Technological frames are composed of "the concepts and techniques deployed by a community in its problem solving" and is made up of "a combination of current theories, tacit knowledge, engineering practice (such as design methods and criteria), specialized testing procedures, goals, and handling and using practice." (Bijker 1987, 168) The notion of technological frame applies to the interactions between various social actors, who may have divergent opinions about the meaning of a particular technological artifact. Technological frames "can be used to explain how the social environment structures an artifact's design" and "how existing technology structures the social environment." (Ibid. p. 173) Technological frames do not structure the interactions between members of particular social groups completely, since the latter have different degrees of inclusion in technological frames and may be members of more than one technological frame. (Ibid.)

Social actors outside of the technological frame populated by the hydraulic engineers at Deltares indeed appear to have different priorities and interests. As I have shown, hydraulic engineers at Deltares persistently try to stay in control of their simulations and models. Reflexivity and critical use is not an antidote against epistemic opacity, but does imply a form of engagement with epistemically opaque simulations and models that can reveal the shortcomings of simulation practice. In the absence of reflexivity and critical use, epistemic opacity is more likely to imply immersion. When models travel outside of their context of development as a result of codification, simulation practice is distributed over a larger and more varied group of social actors (see Humphreys' differentiation between 'individualist' and 'social' epistemologies mentioned in the introduction). These social actors do not always have the desire or the ability to question simulations and models. As hydraulic engineers at Deltares have indicated, the use of blackboxed simulation software sometimes indeed proceeds in a less critical and reflexive fashion. This may not necessarily be the case and I do not wish to condemn all user behavior as 'uncritical', but blackboxed simulation software may imply immersion in ways I show in the following.

3.3 Standing on the shoulders of giants … and then looking the other way?

In this section, I look at the repercussions of the ability of simulations and models to travel outside of their context of development in terms of epistemic opacity and immersion. I study two forms of 'traveling' simulations and models. First, the use of model interfaces, which creates modeling infrastructures where modular model components can be exchanged between simulationists. As a result, simulationists can use these components to build models without having the need to fully fathom the design of the model components they use. The second example concerns the use of simulations and models for purposes of governance, where simulation practice needs to meet requirements related to policy making and decision making. Both examples furnish a social epistemology, since they are no longer bound to their context of development, and are distributed over a larger and more varied group of actors, which may exacerbate epistemic opacity and imply immersion. Members of this larger and more varied group of social actors may no longer be able to fathom the design of simulations and models, or may not wish to approach the latter critically and reflexively due their perceived success.

Modeling interfaces

The year 2001 marked the beginning of HarmonIT, a research program funded by the European Commission aimed at developing and implementing a modeling interface. The development of such an interface was considered necessary to facilitate integrated water management, which requires the modeling of individual bodies of water as well as their interactions.[39] The development of OpenMI (Open Modeling Interface), a modeling interface that enables the exchange of data between different models, sprang from the HarmonIT research program, and is currently carried out by the OpenMI Association. Members of this association include Deltares and a number of other parties, e.g. the Centre for Ecology and Hydrology of the Natural Environment Research Council, Wallingford Software, DHI Water & Environment, and the Centre of Hydrological Information at the National Technical University of Athens. These parties aim to develop the means for integrative water management that can address a large variety of systems, and can also be adapted to the particularities of these various systems. The OpenMI Association concluded that the construction of a single all-encompassing model of all relevant bodies of water would be too costly. In addition, such a model would require a laborious process of negotiation between various parties involved, large amounts of computational resources, and would lead to a model that would be difficult to maintain and understand (in other words, such a model would feature epistemic opacity). Apart from the required integration of existing simulations and models, the OpenMI Association also wishes to enable more flexible forms of simulation practice. Integrated water management "requires the linkage of individual models or model components that address specific domains … the OpenMI has been developed with the purpose of being the glue that can link together model components from various origins." (Gregersen et al. 2007, 175) By acting as a 'glue' between model components, OpenMI provides adaptability of model components that enables the migration of existing modeling systems, which is important "since their re-implementation may not be economically feasible due to the large investments that have been put into the development and testing of these systems." (Ibid.)

OpenMI enables integrated water management by providing a protocol that enables interactions between different model components. Simulationists can develop integrated models by connecting model components that meet the requirements of the OpenMI protocol, which thereby functions as an interface. These model components can then exchange data during run-time. An everyday example of an interface would be the USB interface (commonly recognized by the small horizontal plugs on the end of

[39] The implementation of the Water Framework Directive that I discuss in chapter 5 is another example of integrated water management.

cables of mice, keyboards, etc.), which allows users to connect a variety of devices to their computers, provided these devices meet the necessary requirements. OpenMI-compliant model components that end up in an integrated model can be developed by different parties, represent different processes related to different problem areas (e.g. hydrology, hydrodynamics, ecology, economics, etc.), and may use different dimensionalities (e.g. 1D, 2D, 3D models), modeling principles (e.g. deterministic, stochastic, static), data sources, spatial and temporal resolutions.

The interconnectivity between the components of an integrated model is facilitated by the OpenMI interface and guarantees a degree of adaptability:

> "Model components that comply with this standard can, without any programming, be configured to exchange data during computation (at run-time). This means that combined systems can be created, based on OpenMI-compliant models from different providers, thus enabling the modeler to use those models that are best suited to a particular project." (OpenMI website, retrieved from http://www.openmi.org/reloaded/about/what-is-openmi.php, June 3, 2011)

Thus, models can be linked "with the minimum of re-engineering and without requiring unreasonably high level IT skills." (Moore et al. 2010, 11) The requirements of OpenMI are enabling in the sense that they enhance flexibility and interactivity between model components. However, OpenMI (and interfaces more generally) are also constraining, since they are standards that "impose and enhance particular workflows, thought modes, and modes of interaction upon or in combination with human users." (Cramer & Fuller 2008, 151) Documentation on OpenMI stresses it is an open standard, since its specification and source code are freely available on the Internet, and that it enables connections between different kinds of models, disciplines, and domains.[40] Thus, simulationists using OpenMI compliant models "will be able to 'mix and match' models from different sources." (Moore et al. 2010, 8) Model components can be integrated without formal cooperation among modelers. As a result, engineers may no longer be able to or have the desire to critically reflect on the design of integrated models built using OpenMI-compliant model components.

[40] Note that open source is different from open standards: open source entails making accessible (parts of) computer code, while open standards apply only to interfaces and agreements related to the exchange of software and/or data. Thus, using open standards may still imply the use of 'closed' software.

During a presentation I gave at VORtech (a software development company that specializes in model development and maintenance that is based in *Delft*), several simulationists referred to the aforementioned 'mix and match' approach enabled by OpenMI as 'shopping'. OpenMI enables the exploration and exchange of model components on epistemological 'bazaars'. The software developers at VORtech indicated that OpenMI allows a pragmatic approach in which it is not always possible, nor considered necessary to fully fathom the design of all components of an integrated model. In principle, OpenMI enables the components of an integrated model to exchange data, but in practice it is important to think carefully about the compatibility of model components. Formally, model components are able to exchange data when they are OpenMI-compliant, but the engineers at VORtech do not consider this a guarantee for good results. Some of these model components may be based on radically different approaches to modeling, which makes it crucial to think carefully about the assumptions and ideas that went into them, and the repercussions of connecting these different models. Gerben de Boer expresses his concern about working with OpenMI in a similar vein: "you are no longer forced to think about the work of the other modeler, nor its quality." By taking care of the connections between different model components yourself, "you are forced to examine what the other model is." (Interview Gerben de Boer, June 19, 2009)[41]

In this regard, the OpenMI documentation makes an appeal to the responsibility of simulationists:

> "Note that the OpenMI enables validation by dimension checks on the quantities linked. However, the OpenMI cannot guarantee that the representation of the process in the component or the link to another component is scientifically valid. That is the responsibility of the modeler, model integrator and user." (Moore et al. 2010, 16)

[41] When reviewing this chapter in 2012, de Boer pointed out his ideas regarding this matter have radically changed. The OpenMI protocol forces simulationists to test their code and ensure it meets the requirements for compatibility with other modeling software. In addition, adherence to the OpenMI protocol enhances the accessibility of one's work to others, which can increase the likelihood you receive feedback on your own work that can be used to make improvements. For these reasons, de Boer argues that all models should aim for OpenMI compatibility, or compatibility with other coupling protocols if applicable.

Simulationists need to describe what different model components are linked in an integrated model using a metadata structure that is part of OpenMI. Although documentation is a potential answer to epistemic opacity, day-to-day realities of software development often show there is neither time nor a persistent commitment to carefully document code in high detail and with great consistency.

According to Mark Roest, the Managing Director of VORtech, OpenMI allows simulationists to create a patchwork of models components, which may lead to a fragmentation of their expertise. A simulationist may know very little about, for example, algae blooms, but may still be able to construct a model that describes such phenomena when he or she uses OpenMI-compliant model components. According to Roest, modelers may therefore be less inclined to study phenomena outside of their own domain of expertise. In addition, it may be tempting for modelers to use an already existing model component rather than developing one from scratch. When a particular model component is considered to be reliable, it may be tempting for modelers to stick to that particular model. However, the range of issues where a model component can be used successfully may be limited. This means that in some cases it might be worthwhile to compare the output of different model components: rather than relying on one single model component, it may be worthwhile to experiment with a variety of model components and compare their output from time to time. An integrated model will generate an answer, but whether that answer is correct can be difficult to find out. An open modeling interface is therefore by no means a guarantee for a critical and reflexive attitude towards simulations and models. (Interview Mark Roest, March 5, 2009)

Integrated models may introduce another risk. The design of models consists of a multitude of different interacting processes, such as formalization, parameterization, discretization, and collecting, parsing, mining, and visualizing data. Choices made at a particular stage of designing a model have repercussions for subsequent stages. The patchwork-like character of integrated models has made it increasingly difficult to fathom their design, and implies the possibility that errors only become apparent when the model malfunctions. As a result, epistemically opaque (integrated) simulations and models may lead to what Snook (2000) has called 'practical drift'. In addition, integrated models echo the concerns advanced by Perrow (1999), who argues the tight coupling and interactional complexity of present-day technologies implies accidents are bound to happen at some point (see section 1.2). Paraphrasing Snook, the development of integrated models could imply 'code drift'.

The 'openness' attributed to modeling interfaces deploys a rhetoric that stresses the promising aspects of open source software development, i.e. the exchange of knowledge and expertise and thereby jointly contributing to a collective effort, and escaping the constrictions of commercially developed and proprietary software. Despite the importance of the latter, the patchwork-like character of models built using OpenMI implies epistemic opacity. Integrated models cover up different modeling techniques and may be perceived as properly functioning knowledge instruments. As a result, simulationists may no longer be able to think critically about the models they are constructing and using, or simply no longer have the desire to approach their models critically and reflexively.

Governance simulations

Present-day water governance involves a variety of issues, such as safety, sustainability, logistics, economics, and the preservation of landscapes with historical value. As indicated in chapter 1, water governance is no longer simply a matter of increasing safety: rather than focusing exclusively on preventive approaches to flooding (building, improving, and maintaining flood defenses), approaches to risks have been pushed more and more towards the distribution of responsibilities for harmful events. Present-day political commitments to the development of inclusive water governance and participation entail the desire to extend the use of simulations and models to 'non-specialists', such as social actors working in the field of risk assessment and stakeholders. The ideal of participation appears to be informed by the perceived reliability of simulations and models. As a result, simulations and models used for purposes of governance, or 'governance simulations', have become more popular, since they are seen as instruments of water governance that meet the present-day challenges of flood risk management in the Netherlands.

An example of such a governance simulation is the Maptable, a GIS (Geographic Information System) application that allows users to explore the repercussions of water-related policies for various areas in the Netherlands. As the name of the application implies, the model runs on a computer that is embedded in a table. Model output is presented on a touchscreen that occupies a substantial part of the table's surface. The touchscreen can be controlled by means of a keyboard and pen. Toine Smits and Emiel Kater of the Radboud University in Nijmegen, who contributed to the development of the Maptable and implemented it in the field, explain that the choice for a table is no coincidence. The table provides a familiar setting that allows different users to stand around the Maptable and negotiate on the basis of the visual output presented on the computer screen. Sitting around a table for the purpose of negotiation and collaboration is thus enhanced. The extended range of water-related issues requires the balancing of more and less compatible problems, such as safety concerns and the preservation of landscape. Kater's views resonate with this more inclusive form of water governance. According to him, it will ultimately become possible to use the Maptable to study the interactions between hydrological, hydrodynamic, ecological, and economic phenomena. (Interview Emiel Kater, March 25, 2009) The Maptable allows users to explore and discuss various scenarios related to water governance. A variety of social actors with different aims can thereby engage in communication and collaboration in the field of water governance. The outcome of these interactions can subsequently provide feedback to local decision makers and national policy makers.

Users standing around the Maptable can manipulate the landscape on the Maptable's touchscreen by removing dikes, inserting patches of forest, etc. When they have developed a new landscape according to desires, the Maptable calculates the consequences of the proposed changes in the landscape. Within minutes, users can see a visual representation of the consequences of the decisions they have proposed, which may also include dynamic representations in the form of animations. Integrative water governance harbors many different and complex issues, which requires a lot of computational resources and more powerful computers. The developers of the Maptable stress the importance of quickly delivering feedback to users: if it takes too long for Maptable to produce output, users will simply lose interest. Due to the complexity of water governance and the challenge of capturing and keeping the attention of the audience, it may not be feasible to perform highly detailed calculations on the spot.

Though the amount of time it takes for a relatively complex hydrological or hydrodynamic model is small compared to the early days of computational modeling, the need for the Maptable to quickly deliver output requires the simplification of the calculations underlying its representations. Toine Smits and Emiel Kater admit that this might introduce blind spots, but also stressed that the main aim of the application is to provoke debate and not to provide the means for elaborate representations. As a result, providing users with an interactive and immersive experience introduces serious simplifications, which have an impact on the content of participatory water governance that the Maptable aims to establish. A further restriction of the content of water governance is the design of applications running on the Maptable. The various ways in which users can develop scenarios are shaped by decisions made by the Maptable's developers. These decisions might also incorporate the ideas of decision makers and policy makers about water governance into the Maptable's design.

The design of the Maptable apparently shapes integrated water governance in ways discussed above. This leads to the question whether the Maptable's users have the ability to critically engage its design, or express the desire to do so. Although hydraulic engineers may have a more humble expectation of the potential of simulations and models to explore target systems, it is not certain whether users of simulations and models share their point of view. The difference in the priorities of hydraulic engineers engaged in basic research and those of users working with a particular model may turn out to be difficult to bridge. This may be due to differences in expertise, but also because users of simulations and models may work in a context where a critical and reflexive approach to simulation practice is not always considered important, or may simply be incompatible with the interests of those involved. The uncritical adoption and use of epistemically opaque governance simulations may imply immersion.

Governance simulations are relatively accessible, especially in comparison with earlier forms of modeling that were restricted to hydraulic engineers. However, the accessibility of governance simulations does not necessarily endow an extended audience with a detailed understanding of the various challenges of integrated water governance. This is not a property of software design per se. As Wardrip-Fruin (2009) shows, computer games that remain sufficiently transparent may allow users to gain knowledge of the design of these games and reflect on it. Computer games designed according to this principle "create a surface-level experience that will make it possible for audiences to build up an appropriate model of the system internals" (Ibid. p. 300) This so-called 'SimCity Effect' (named after a popular computer game that is representative of the kind of interaction Wardrip-Fruin discusses here) "leads to audience understanding of the operations of an underlying system." (Ibid. p. 420) However, I hasten to add that new and improved designs do not necessarily provide a solution for the potentially dangerous effects of epistemic opacity: new and improved designs by no means guarantee different user behavior.

Conclusion: epistemic opacity or reflexivity?

Since the world is not predictable but has to be made such, what is considered to be at risk depends on processes of knowledge production. Hydraulic engineering can be understood as a site of knowledge production, which is made subject to control by means of computational approaches to hydrological and hydrodynamic phenomena that aim to make risks tractable. Control thus implies protection, but also a state in which technological cultures may be rendered vulnerable due to the inscriptive aspects of simulations and models. In that sense, control can involve both lack and excess: technological cultures may be at risk due to a lack of knowledge. However, an excessive desire to make risks tractable may stifle the acquisition of knowledge about risks. As I have shown in chapter 1, studies of risks will often point to accidents as events of slippage where this lack and excess of control can become apparent. My aim is not so much a study of such accidents, but rather the repercussions of the production of knowledge that aims to understand, predict, and counter risks. Simulation practice can be analyzed as a form of knowledge production by studying the actions of simulationists and other social actors working with simulations and models, and the investments that flow through the latter. Such an approach entails that simulations and models are not critiqued only in terms of what they do or do not represent. Merely lamenting the inscriptive effects of simulations and models will yield a rather one-sided interpretation, which may be tantamount to accusations of immersion (see section 2.3).

Over the course of this chapter I described the development of the experimental apparatus of hydraulic engineering. After a period of co-existing modeling techniques that responded to various institutional and socio-political challenges, managerial decisions and the reflexive and critical adoption of computational modeling established the computer as a dominant knowledge instrument in hydraulic engineering. The dominance of computational modeling has made it more and more difficult for hydraulic engineers to fully grasp the design and impact of the simulations and models they use. In addition, computational methods enable codification. This allowed simulations and models to travel outside their context of development, and distributed simulation practice over a larger and more varied group of social actors. Present-day developments in simulation practice, such as modeling interfaces and governance simulations, further establish social epistemology as a dominant form of knowledge production.

The increasing complexity of simulations and models, together with their codification in the form of computer software that has a larger and more varied audience, imply issues related to epistemic opacity: simulationists and other social actors may no longer be able to deal with simulations and models reflexively and critically, or may not have the desire to do so. Those immersed in simulation practice straddle discovery and manipulation. According to Turkle (2009) and Sennett (2008), this balancing act between discovery and manipulation is tipping more and more towards manipulation, since epistemically opaque technologies imply a disconnection between mind and hand. Turkle sees this disconnection as a defining characteristic of present-day simulation practice. Both Turkle and Sennett argue present-day technologies stress the need for a more 'craft-like' approach. However, this call for craftsmanship is problematic for two reasons.

First, it is unlikely that simulationists will ever completely master their simulations and models. Indeed, it is difficult to envision a form of simulation practice that does not feature some degree of epistemic opacity. Immersion is related to present-day and previous forms of simulation practice alike. Simulation practice prior to the advent and adoption of computational modeling may suggest hydraulic engineers were more familiar with their topic of study and instruments. For example, the use of scale models was dominant at an early stage before the codification of tacit knowledge, scale models are made of the same material as the topic of study, and scale models forced hydraulic engineers to stay close to the workings of the model (sometimes quite literally, as is suggested by figures 3.1 and 3.2). However, hydraulic engineers struggled with early forms of simulation practice as well: the lack of codification was also due to a lack of knowledge about hydrological and hydrodynamic phenomena, the use of scale models was accompanied by scaling effects that were relatively unknown at the time, and early forms of simulation practice indicate a social epistemology as well, e.g. the differentiation between hydraulic engineers, construction workers, and employees taking measurements (which were often women at the time). In this sense, social epistemology is a trait of early and present-day forms of simulation practice.

Although epistemic opacity accompanies present-day simulation practice, it is not a given that reflexivity is waning and that simulationists fall prey to immersion as a result. Hydraulic engineers do not object to codification per se, but do stress it should not lead to uncritical adoption of model output. The 'craft of modeling' I described earlier can be seen as a form of reflexivity that results in an engagement with the epistemic opacity that is characteristic of simulations and models. Hydraulic engineers attempt to 'tease out' knowledge from simulations and models, i.e. by using them as 'sparring partners'. The answer to epistemic opacity and the danger of immersion is then not so much the mastery of simulations and models, but rather reflexivity leading to the adoption of a 'craft-like' approach to simulation practice. This perhaps suggests a different explanation of craftsmanship, which does not emphasize mastery, but looks at tinkering as a promising form of engagement with epistemically opaque technologies.

A second reason to problematize the aforementioned call for craftsmanship is that it may be impossible to reverse the trends that have established epistemically opaque simulation and models. Although the danger of epistemic opacity was signaled in the early days of software development (see for example Dijkstra 1987), present-day challenges of hydraulic engineering do not bode well for Dijkstra's suggestion to "confine ourselves to the design and implementation of intellectually manageable programs." (Ibid. p. 26) Today, hydraulic engineers at Deltares are often committed to codification, provided it is based on successful application and a reflexive approach to simulation practice more generally. In addition, codification is also a response to the need for Deltares to market its expertise and thereby enhance it economic sustainability, and the socio-political need to deal with increasingly complex issues.

In sum, simulation practice features epistemic opacity and reflexivity. Epistemic opacity cannot be ruled out, but may lead to immersion in the absence of reflexivity. Studies of simulation practice concerned with immersion should not focus on epistemic opacity exclusively, but should also inquire into the reflexivity of simulationists and other social actors involved with simulation practice. The various ways in which engineers at Deltares care for their instruments are informative in that regard, and indicate the value of ethnographic studies of technological practices and immersion more generally. Issues related to epistemic opacity will return in the following chapters. When model output is considered to be reliable, those involved with simulation practice may be less inclined to question the authority of simulations and models. In chapter 4, I show how knowledge produced in simulation practice comes to be perceived as reliable by different social actors. These social actors differ in terms of their willingness and/or ability to question the perceived reliability of simulations and models. What is more, simulation practice increasingly involves the design of communicative spaces where knowledge is exchanged among different social actors. In chapter 5, I look at how simulations and models establish such communicative spaces, and examine whether various social actors engage the epistemic opacity of these simulations and models.

4. Validating models in the face of uncertainty: geotechnical engineering and dike vulnerability

Introduction

The geographical position of the Netherlands makes it crucial to monitor the status of flood defenses that protect the Dutch against water from the North Sea, *Waddenzee*, the major rivers (*Rijn*, *Maas*, *Lek*, *Waal*, and *Merwede*), the *IJsselmeer*, and *Markermeer* (see map on page 13). Periodic assessments of flood defenses are anchored in Dutch law through the *Wet op de Waterkeringen*, or Flood Defenses Act, a set of regulations that prescribes that parties responsible for managing the primary flood defenses carry out safety assessments every six years to make sure whether the dikes, dunes, and hydraulic structures (e.g. sluices) meet statutory safety requirements.[42] The *Wettelijk Toetsinstrumentarium* (literally Legal Assessment Instruments, WTI) prescribes the assessment criteria and techniques. The WTI is administered by the Ministry of Infrastructure and the Environment, and consists of two components. First, the *Hydraulische Randvoorwaarden* (Hydraulic Boundary Conditions, HR) provide statutory descriptions of the loads (e.g. waves, water levels, and tides) that flood defenses need to be able to withstand. Second, the *Voorschrift Toetsen op Veiligheid* (literally Prescription Assessment for Safety, VTV) determines which testing methods and calculation rules need to be used during the safety assessments of flood defenses.

Two different assessment bodies carry out the safety assessments: the Water Boards[43] take care of 90% of the flood defenses. The Directorate-General for Water Affairs (DG Water) that is part of the Ministry of Infrastructure and the Environment takes care of the remaining 10% (Transport and Water Management Inspectorate 2006, 5). The assessment bodies send their reports to the provincial authorities, which coordinate, supervise, and report the activities of the assessment bodies to the Minister of Infrastructure and the Environment. Subsequently, the Inspectorate for Transport, Public Works and Water Management performs an evaluation to ensure that the safety assessments of flood defenses meet regulatory demands. The outcome of the

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[42] Since this chapter will be largely devoted to the study of dikes, the assessments of dunes and hydraulic structures will be largely left out.

[43] The Water Boards (*waterschappen* or *hoogheemraadschappen*) are regional authorities that take care of the maintenance of flood defenses, waterways, water quality, and sewage treatment. There are currently 25 Water Boards in the Netherlands. The history of the Water Boards goes back to the 13th century when they developed an elaborate scheme of taxes and governance structures. The Water Boards are credited as being the oldest form of democratic governance in the Netherlands.

assessments is summarized in order to draw a national picture. To that end, the assessments are analyzed and main findings are sent to the Minister of Infrastructure and the Environment. Finally, the Minister informs the Parliament about the outcome of the safety assessments, and proposes a program for improvements, the *Hoogwaterbeschermingsprogramma* (Flood Protection Program, or HWBP).

To improve the accuracy of the safety assessments of flood defenses, the VTV and HR are revised every assessment round so that the safety assessments of primary flood defenses are based on the latest available knowledge about critical conditions and dike failure mechanisms – processes responsible for damaging a dike's structural integrity to such an extent that it fails, in some cases leading to reduced ability to protect against floods, or even complete failure due to dike breaches. DG Water organizes and administers a research program to improve the HR and VTV known as *Sterkte en Belasting Waterkeringen* (Strength and Load Water Barriers, SBW). The supervision of SBW has been delegated to the *Waterdienst*, the branch of *Rijkswaterstaat* responsible for the execution of policies in close cooperation with knowledge institutes and engineering consultancies. Research for the SBW program is largely carried out by Deltares. Commercial engineering consultancies take care of about one fifth of the research. Members of the assessment bodies and DG Water review the results of the SBW program for Water Affairs. The *Expertise Netwerk Water* (Expertise Network Water, ENW) and other expert bodies provide additional external reviews. Ultimately, the DG Water decides which parts of the WTI are in need of further scrutiny. The safety assessments of flood defenses have a cyclic character since the output of every assessment process provides the input for the subsequent assessment process. Thus, the SBW program may generate knowledge that can lead to updates in the WTI, which can be revised and used in subsequent assessment rounds.

According to the 2006 results of the second safety assessment of the primary water defenses, also known as the *Landelijke Rapportage Toetsing* (National Assessment Report, LRT), presented in figure 4.1, 24% of the Dutch primary flood defenses did not meet the statutory requirements of the HR and WTI at that time ('voldoet niet aan de norm' meaning 'does not meet the standard'), while 44% of the primary flood defenses did meet those same requirements ('voldoet aan de norm' meaning 'meets the standard'). For the remaining 32%, the verdict 'geen oordeel' or 'no judgment' applied, since "[t]he managing authority, for whatever reason, was unable to gather sufficient data or the set of instruments available was insufficient to be able to fully carry out the assessment." (Transport and Water Management Inspectorate 2006, 6)

Figure 4.1 Resultaten tweede veiligheidstoetsing primaire Waterkeringen, 1 januari 2006 (Results of the second safety assessment of the primary water defenses, 1 January 2006). Source: Deltacommissie 2008, 20. © Synergos Communicatie.

An important motivation behind the SBW program is ensuring that the safety assessments of flood defenses can be performed accurately and that blind spots are removed, thereby reducing the amount of flood defenses that fall into the category of 'no judgment'. An overly unfavorable picture of dike safety leads to a waste of resources and an image of risk and danger that is exaggerated. An overly favorable picture veils potential vulnerabilities. Blind spots in safety assessments point to a lack of knowledge, which could give rise to political issues regarding responsibility and credibility. In the light of these results, the extent to which the Dutch have mastered their environment may seem problematic, since a large percentage of Dutch dikes might be at risk.

Modeling is a major component of research carried out in the context of SBW that is meant to gain or enhance understanding of dike failure mechanisms. Thus, models fulfill a crucial role in countering the large amount of dikes that fall in the category 'no judgment' by producing or updating knowledge about dike failure mechanisms. Without substantial knowledge of a dike failure mechanism, it is difficult to understand what constitutes critical conditions for dikes, and how the latter may fail. Thus, both components of the WTI (the HR and VTV) can be revised due to the results of the SBW program. In addition, unexpected events form an important incentive to revise both the HR and VTV. Certain dike failure mechanisms may turn out to be more important than expected or may simply be relatively unknown, as is shown in the following discussion on 'piping' (a dike failure mechanism that features prominently in present-day research carried out in the context of the SBW program). Ideas about critical conditions are based on data about water levels that dates back a couple of centuries at most, and may thus be a mere statistical regularity that may need to be revised in the light of the unexpected. As argued above, hindsight is always 20/20. One way safety assessments take such uncertainties into consideration is the use of extreme boundary conditions.

In this chapter, I look at how simulations and models are used to counter the large number of dikes that fell under the 'no judgment' category in the LRT of 2006, and how the use of geotechnical simulations and models affects and is affected by Dutch dike safety policies. Dikes are "thick with politics" indeed (Bijker 2007b), as is the production of knowledge about dike failure mechanisms, which features a deep intertwining of technological, institutional, and socio-political aspects of water management in the Netherlands.

Validation: model truth and model reliability

The process of validation is of vital importance in assuring whether geotechnical models provide an accurate image of the safety of flood defenses. More generally, validation of models is aimed at ensuring they correctly reproduce the behaviors of the real-world systems. Validating models involves calibration, an iterative process of comparing the model output with the behavior of the system in question, and using the discrepancies between model output and system behavior to improve the model. This process is repeated until the accuracy of the model is considered acceptable for the issue at hand. Note that validation is different from verification. Whereas the former is concerned with building the right model, the latter is concerned with building the model right. Verification entails making sure models perform as intended, e.g. by comparing conceptual models to computer simulations that implement these models.

Studies of simulation practice have highlighted the pragmatic and contextual considerations that shape model validation. Morgan and Morrison (1999) argue the representative power of simulations and models should not be interpreted in terms of mirroring or mimesis, but with close attention to practices: "[w]e do not assess each model based on its ability to accurately mirror a system, rather the legitimacy of each different representation is a function of the model's performance in specific contexts." (Morgan & Morrison 1999, 28) Oreskes et al. take a comparable contextual and pragmatic approach to model validation: "the term validation does not necessarily denote an establishment of truth (although truth is not precluded). Rather, it denotes the establishment of legitimacy, typically given in terms of contracts, arguments, and methods." (1994, 642) In the case of computer simulations, Küppers et al. (see section 2.2) stress that the aim cannot be the reproduction of real-world systems, since "computer simulations are not numerical *solutions* of a theoretical model. Rather, they employ a *generative mechanism to imitate the dynamic behavior of the underlying process*." (2006, 11, original emphasis) However, as will become clear, computer simulations do fulfill a representational function in practice, and are endowed with the ability to describe certain characteristics of real-world systems.

Similar pragmatic and contextual concerns reverberate in the discussion in section 2.2, where I argued that simulations and models have a range of explanatory functions. For example, they can be celebrated for their potential to facilitate understanding of complex systems, to predict phenomena, and to formulate theories. Similarly, the study of modeling practices in hydrology and hydrodynamics in chapter 3 emphasized not so much notions of positivism and realism among engineers, but rather a craft-like and exploratory process of tinkering. The successful application of models in a particular context yields reliability rather than a strict notion of truth (Winsberg 2006). Outside the realm of these engineering practices, model output can be taken literally more easily depending on the degree of inclusion (Bijker 1987, see section 3.2) of social actors in technological frames where simulation practice fulfills an exploratory role. The functions simulations and models fulfill are shaped by the interests of the social groups that deploy them, and the different kinds of simulations and models these social groups have at their disposal. Rather than focusing on model construction, as I did in chapter 3, this chapter looks primarily at how models become reliable or even 'true' according to various social groups. A focus on relevant knowledge rather than truth is an important characteristic of the work of STS scholars (see section 2.3), who argue the objectivity of science is not so much an explanation for the validity of knowledge but rather needs to be explained itself. STS is dedicated to showing how interests, technologies, and practices are intimately intertwined. Rather than asking whether knowledge is true, STS scholars ask questions of relevance aimed at finding out for whom particular forms of knowledge are important, how this knowledge is produced, and how technological, institutional, and socio-political aspects of knowledge production shape simulation practice.

Research questions and chapter overview

The goal of this chapter is certainly not to unmask (geotechnical) modeling as an epistemological jester, e.g. by emphasizing the dangers that simulations and models pose since real-world phenomena are staged in modeling practices, but rather to show how various social groups deploy models to produce knowledge relevant to them. In the practices of these social groups, models become true by virtue of providing some relevant contribution to the problem of dike safety in the Netherlands. The main questions this chapter addresses are as follows: how do simulations and models contribute to producing knowledge about dike failure mechanisms that is seen as relevant by different social groups, and how may the various ways in which these social groups deploy geotechnical models put the Netherlands at risk?

The three sections of this chapter each engage a different aspect of geotechnical modeling in the context of the safety assessment of flood defenses in the Netherlands. Section 4.1 describes how geotechnical modeling takes place in the laboratory. I focus on the dike failure mechanism piping for two reasons. First, although dikes in the Netherlands are particularly vulnerable to piping, as was established by earlier research in the 1980s and 1990s, piping became a particularly pressing issue in 2005. This leads to the question how piping ended up on the agenda of geotechnical research. Second, piping is a dike failure mechanism that geotechnical engineers struggle to understand. Although research on piping relies heavily on observational knowledge and exploratory experiments in the laboratory, calculation rules need to be and are indeed developed in order to revise the WTI. The various ways in which knowledge about piping travels outside the laboratory will be addressed throughout this chapter. In section 4.2 I focus on the use of computational power and large data sets that are seen as important means to understand dike failure mechanisms. I discuss how computational power, sensor technologies, and large data sets contribute to the validation of geotechnical models. In this section I also discuss how attempts are made to transfer knowledge about geotechnical phenomena (e.g. piping, but also other dike failure mechanisms) to the context of risk monitoring and decision making. A current trend underlying this transfer is a form of flood risk management that emphasizes the use of software applications, such as interactive visualizations and serious games, to allow decision makers, policy makers, and stakeholders to deal with the onset and consequences of dike breaches. In section 4.3 I look at the different approaches to dike-related risks in the Netherlands, and to what extent knowledge acquired by means of geotechnical models is incorporated into Dutch dike safety policies. Debates about flood risk management in the Netherlands show how various forms of flood risk management relate to each other, and how this creates a pretext for the development and use of geotechnical models.

Throughout the chapter, the issue of uncertainty will surface as a crucial side effect of simulation practice that may put the Netherlands at risk. Uncertainty is usually defined as a lack of knowledge, which would make the term synonymous with inaccuracy (Petersen 2012, 49; see also Kouw et al. 2013), but the discussion of geotechnical modeling in this chapter reveals other meanings that can be attributed to the concept. I adopt Gross' definition of uncertainty (which was also mentioned in section 1.2) as "a situation in which, given current knowledge, there are multiple possible future outcomes." (Gross 2010, 3) During my discussion of model validation, I elaborate on various forms of uncertainty that emerge in geotechnical modeling. In addition, I elaborate on the consequences of these various forms of uncertainty for geotechnical engineering in the conclusion.

4.1 Piping

Geotechnical engineering is a subdiscipline of civil engineering that focuses on how constructions (e.g. dikes, dams, pipeline systems, tunnels, and foundations of buildings and bridges) react under various circumstances, and whether the structural integrity of such structures can be preserved in case stress is exerted upon them. In their work, geotechnical engineers apply insights from the scientific discipline known as 'soil mechanics'. Karl von Terzaghi defined soil mechanics as

> "the application of the laws of mechanics and hydraulics to engineering problems dealing with sediments and other unconsolidated accumulations of solid particles produced by the mechanical and chemical disintegration of rocks, regardless of whether or not they contain an admixture of organic constituents." (Terzaghi 1943, 1)

Equipped with the insights from soil mechanics, geotechnical engineers study dike failure mechanisms. For example, in the case of 'overtopping', water may flow over the top of a dike (also known as the dike's 'crown') to low-lying areas, damaging the dike's slope on the land side. This can lead to gradual erosion of material used to protect the dike's slope, eventually causing a dike to fail. During the 1953 flooding of *Zeeland* that featured a rare combination of high tide and wind from the sea, overtopping was the main reason why many dikes failed. Man-made structures (e.g. pipes), animals, roots, or collisions with objects floating in the water, such as ice or ships pose additional threats to the structural integrity of dikes.

The aforementioned dike failure mechanism piping is a form of seepage erosion involving the movement of water under or through a dike that provokes instability, in some cases leading to dike breaches. The flow of water under or through a dike may build channels that can eventually form a shortcut between the dike's water side and land side that runs through the dike or its foundations. Such shortcuts dramatically increase the speed of erosion, which may damage the dike or its foundations to such an extent that the dike collapses or breaches. In the Netherlands, many dikes consist of clay and/or peat that sit on foundations of sand, particularly in the area of the main rivers of the Netherlands. Such dikes are often made of clay or peat and sit on top of sand. Since clay and peat are cohesive and relatively impermeable and sand is relatively permeable, many dikes in Netherlands are prone to seepage erosion of their foundations.

It should be noted that the composition of dikes and their foundations, as well as the interactions between different types of soil in dikes and their foundations, are a source of uncertainty in geotechnical engineering. The composition of soil may be known at location where measurements have been taken, but soil can be rather heterogeneous, implying large differences between measuring points, even those relatively close to each other. In addition, geotechnical engineers stress the difficulties imposed by the complexity of interactions between different kinds of soil. Such interactions are not understood very well yet, and remain a source of uncertainty. The lack of data about soil can be solved in principle, but certainly not in practice given the limited amount of resources for measuring and the fact that some locations may not be accessible (e.g. due to roads, houses, etc.). The various ways in which geotechnical engineers deal with the uncertainties posed by the complexity of soil morphologies will be a recurring theme throughout this chapter.

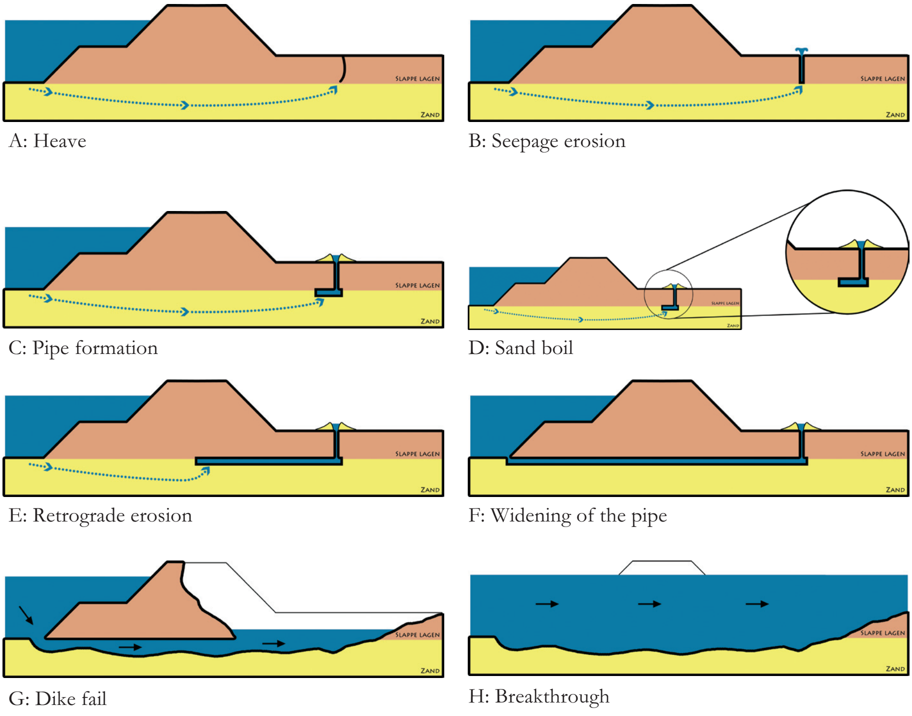

Figure 4.2 Stages of the dike failure mechanism ‘piping’. © Deltares.

Figure 4.2 shows the different stages of piping. The onset of piping is related to high water pressures, which are caused by a large difference between water levels on the water side and water levels on the land side, the so-called ‘hydraulic head’. The larger the hydraulic head, the higher the water pressures in the foundations of the dike. Note that the composition of the dike’s foundation is of vital importance here: water pressure can easily be transferred through the permeable sand layer. Nevertheless, the dike’s foundations provide resistance to the rising water pressure, but in some cases the hydraulic head becomes so large that the water will be forced up, leading to fractures in the top layer - a phenomenon known as hydraulic fracturing or 'heave' (figure 4.2a).

The fractured layers of soil allow for seepage erosion that forms a channel, which is further eroded by the increased water pressure that is due to hydraulic head (figure 4.2b). At the beginning of the 20th century, the British Colonel Bligh concluded that the loss of hydraulic head is proportional to the distance water travels, or creep length. Therefore, Bligh argued, increasing the creep length is an important way to decrease the risk of seepage erosion (Bligh 1910). This is not always feasible in the densely populated regions where dikes are often located. However, another way to counter hydraulic head is the construction of banks that increase the weight of the top layer, leading to more counter pressure and the prevention of heave.

Due to seepage erosion, sand is transported from the dike's foundations to the land side of the dike: a pipe is born (figure 4.2c). Depending on the persistence of hydraulic head and the characteristics of the dike's foundations, the pipe will start transporting sand to the land side of the dike, creating a crater of sand that is also known as a 'sand boil' (circled in figure 4.2d). For dike watchers who patrol the Dutch dikes on a regular basis, sand boils are visual proof of seepage erosion.

When the transport of sand is continuous, the pipe will grow towards the water side of the dike in a process known as 'retrograde erosion' (figure 4.2e). This process gradually builds a network of channels in the dike's foundations. These channels can remain in place due to the cohesive properties of the layer on top of these channels. When the pipe grows, water pressure inside the pipe also decreases due to the distance from the initial seepage erosion channel created by hydraulic fracturing (figure 4.2a and 4.2b). The process of piping may thereby cancel itself out. However, if the hydraulic head provides sufficient water pressure, a pipe through the dike's foundations between the land side and the water side may be formed (figure 4.2f). A shortcut between both sides of the dike is thereby created, widening the pipe, accelerating the process of erosion, and leading to failure of the dike (figure 4.2g). Two events can lead to a dike breach: water can flow either through the dike since its structural integrity is damaged, or the dike may collapse, leading to overtopping and a subsequent breach (figure 4.2h).

Modeling piping: a short history

In order to gain an understanding of the behavior of soil, geotechnical engineers often rely heavily on experiential knowledge. In the early days of geotechnical engineering in the early 20th century, it was not uncommon for geotechnical engineers to smell or even taste samples in order to figure out the composition of the sample in question and judge the shape of soil particles - a practice that the older generation of geotechnical engineers at Deltares remembers vividly. Although piping has been observed in the field, there are only a few detailed accounts of the process. More importantly, most of the piping process is inaccessible to the human senses, since it takes place inside a dike. In the work of Hans Sellmeijer of Deltares, who conducted research on piping in the 1980s, visual observation is an important source of knowledge on piping: "[a] certain amount of simplification has to be introduced so as to make the problem suitable for mathematical analysis. Inspiration is drawn from simple visual tests." (Sellmeijer 1988, 2)

After foundational work in the early 20th century that relied heavily on empirical observations (e.g. the work of Bligh, which is mentioned above), research on piping by means of models started in the Netherlands in the late 1970s. Simulations and models provided important extensions of the human senses, allowing geotechnical engineers to study phenomena otherwise inaccessible to them. Models of dike foundations on different scales provide the means to study the conditions that provoke piping, how piping proceeds, and what conditions influence the onset and process of piping, e.g. the composition of the dike's foundations and the hydraulic head. Differences in the shape and size of grains constitute different types of sand, which also behave differently. In the 1990s, laboratory experiments were conducted in order to validate calculation rules developed by Sellmeijer. These experiments were carried out using a cross-section of the foundations of a hypothetical dike (figure 4.3). A Plexiglas window covers the cross-section so that the process of piping can be observed. Water pressure is exerted on one side of the cross-section to simulate the hydraulic head that provokes the process of heave and subsequent onset of piping. On the other side, a part of the cross-section is covered with a counter-weight to simulate the pressure exerted by the top layer of the dike. Part of the cross-section on the right-hand side is left open to simulate the presence of a ditch, which can form a way for the water to come to the surface due to water pressures exerted by the hydraulic head.

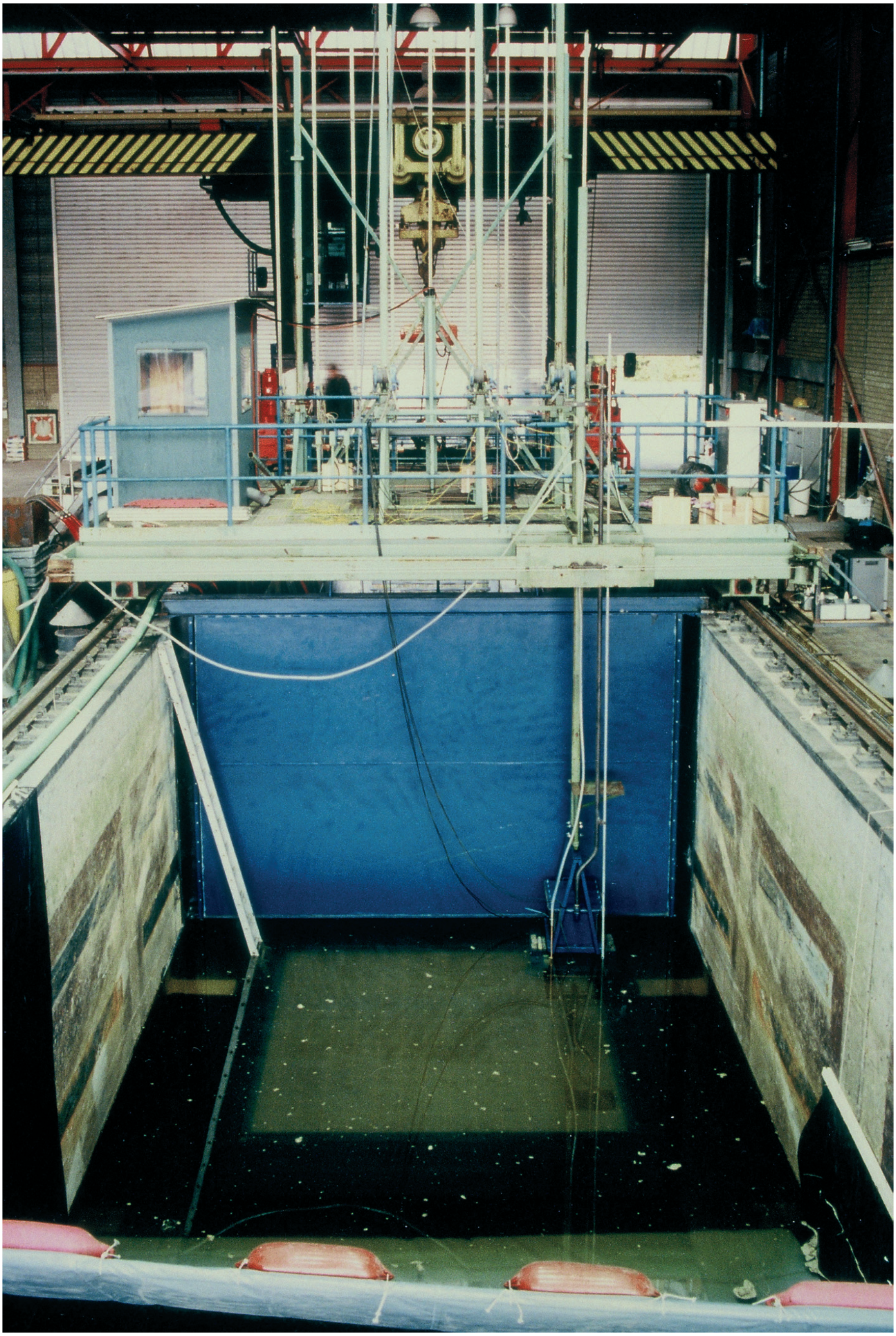

Figure 4.3 Research on piping in the *Deltagoot* in 1990. Source: https://beeldbank.rws.nl, Rijkswaterstaat / Joop Weijers

The experiments in the 1990s confirmed Sellmeijer's predictions that the growth of piping could be stopped due to the resistance of the soil in the dike's foundations. Sellmeijer calls the hydraulic head right up to the point where piping or heave occur the 'critical head' (Technical Advisory Committee on Flood Defenses 1999, 11), which denotes a state of equilibrium where sand inside a pipe does not move. In case the hydraulic head is smaller than the critical head, the pipe will not increase in size. However, the experiments were not carried out to the point of retrograde erosion leading to a 'full' pipe acting as a shortcut between the water and land side of the dike, since this would damage the experimental setup too much (Vrijling et al. 2010, 41). As a result, the hydraulic head that would provoke retrograde erosion was not determined.

The use of Sellmeijer's calculations to determine critical head was further complicated by the fact that they required data about the morphological properties of soil that can be very difficult to determine. The critical head is influenced by the thickness of the sand layer and top layer in question, the permeability of the sand layer, and soil morphology (e.g. size and shape of sand grains). Sellmeijer's initial calculations assumed the homogeneity of soil. The experiments in the 1990s were used to estimate input values for safety assessments in which Sellmeijer's calculation rules were used extensively. However, the fact that the calculation rules assumed homogenous soil and the lack of data about soil properties formed a source of uncertainty in the process of applying Sellmeijer's calculation rules in safety assessments.

After the groundbreaking and foundational work of Sellmeijer, piping found its way back to the research agenda of *Rijkswaterstaat* as a result of being earmarked as a problem deserving further examination. An important influence in this was the outcome of *Veiligheid Nederland in Kaart* (Mapping the Safety of the Netherlands, or VNK), a collaboration between the Ministry of Infrastructure and the Environment, the Water Boards of the Netherlands, and the *Interprovinciaal Overleg* (a foundation comprising the provinces of the Netherlands as members). VNK is aimed at representing flood risks in terms of economic damage and casualties using "innovative methods". ("Veiligheid Nederland in Kaart." Helpdesk Water. Accessed September 10th, 2011. http://www.helpdeskwater.nl/onderwerpen/waterveiligheid/veiligheid-nederland/)

The first phase of VNK took place between 2001 and 2005, and concluded that piping posed a substantial risk to dike safety in the Netherlands (Rijkswaterstaat 2005, 90). Remco Schrijver, Project Manager of SBW at *Rijkswaterstaat*, points out that the insights that came out of VNK did not correspond to the experiences of the dike managers: "I do not think there was the realization that the problem was *that* big." (Interview Remco Schrijver, August 11, 2011) "The great difference of course", Schrijver adds, "is that the VNK calculations are based on water levels that we have never seen. That is the case with these boundary conditions, so you get completely different results." (Interview Remco Schrijver, August 11, 2011) The SBW program addressed the question whether piping posed a real threat: did the dike managers have an incorrect view of piping-related risks, or was the dramatic picture that came out of the first phase of VNK only due to the schematizations that were used to calculate piping-related risks? Schrijver's comment on the outcome of VNK indicates that the boundary conditions used for the calculations were partly responsible for its dramatic outcome. However, Schrijver does speak of the issue in terms of something that is 'really' a problem. The calculations used in VNK might use hypothetical boundary conditions, but their use has had very concrete repercussions.

In 2004, the year before the results of the first round of VNK became public, Vrijling et al. (2004) had already urged the various parties involved with VNK to re-examine the calculation rules to determine piping-related risks. During the first phase of VNK, the shortcomings of Sellmeijer's method had become the subject of debate. The assumption of homogenous soil was considered problematic in the light of the heterogeneity of dike foundations. When the use of Sellmeijer's calculation techniques led to high estimations of dike failure due to piping, the various parties involved with VNK found it necessary to improve these calculation rules. For the second round of VNK, the ability to model two layers was added to Sellmeijer's calculation rules (Vrijling et al. 2010, 12). Still, *Rijkswaterstaat* concluded that more research on piping was necessary to assess the reliability and improve the accuracy of Sellmeijer's calculation rules. Subsequently, piping found its way into the SBW program. The new and improved calculation rules that would be the outcome of this research could be included in the dike safety assessment round starting in 2012. Much of the research into piping took place at Deltares, where experiments in the laboratory provided the means to validate existing methods to calculate piping-related risks.

Small- and medium-scale experiments

When the new round of research into piping commenced in 2007, experiments similar to those in the Deltagoot were carried out on small-scale (figure 4.4) and medium-scale (figure 4.5) models. An important motivation behind these experiments was the fact that very few aspects of the piping process had actually been observed in the past.

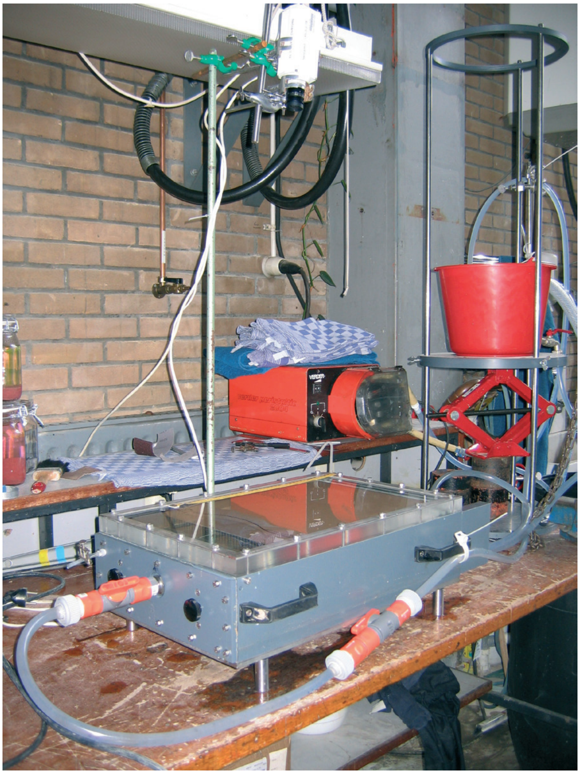

Figure 4.4 Model used for small-scale piping experiments. Photo by Vera van Beek. © Deltares.

When I attended an experiment using a medium-scale model, I was introduced to some of the challenges faced by the geotechnical engineers at Deltares who study piping. The medium-scale model used during the experiment was covered with a thick sheet of black plastic in order to keep sunlight out and minimize reflections on the Plexiglas sheet that covered the layer of sand that was studied. Light and reflections can compromise the quality of the camera recordings used to capture the process of piping. The lamps used to illuminate the experiment generated heat, making the experience of tracing movements of individual grains of sand even more demanding. More than once, a moving grain of sand was a source of modest celebration or at least a welcome change in an otherwise not very eventful experiment. When I found myself concentrating on the movement of individual particles, and studying how the meandering flows of water created small channels that would sometimes disappear soon after, I remarked that the experiment has a meditative aspect to it, which did not really resonate with the experimenters. When the experiment was not very eventful, the water pressure that simulated the hydraulic head would be increased. This was usually not done according to an exact and elaborate protocol, but rather in order to provoke some kind of event, e.g. moving grains of sand or the buildup of meandering channels. An important part of the experiment was provoking some worthwhile event that would enable some understanding of a complex system. Arriving at an understanding of piping in this case involved, quite literally, sandboxing.[44]

Figure 4.5 Model used during medium-scale piping experiments. The model is shown without the plastic cover mentioned in the text. Photo by Vera van Beek. © Deltares.

Initially, small-scale experiments did not corroborate Sellmeijer's theory that the growth of pipes may stop, since all small-scale experiments eventually led to fully grown pipes. However, medium-scale experiments did show that the growth of pipes can come to a halt. Vera van Beek, who conducts extensive research on piping in the context of SBW at Deltares, found that the models on different scales behaved "more or less the same", but also found that

[44] In software development, sandboxing is a term that describes the creation of testing environments in which applications or procedures can be used in a space dedicated to testing. This is typically done in case running the applications in their intended context might cause too much damage.

> "there are differences if you study [the models] more closely … the small-scale experiments, in some cases, featured a network of branches instead of a single straight channel, so yes, there were differences. In the end we did not do anything with [these differences] since two experiments we considered identical also featured different patterns, so we think these processes are governed by micro-scale heterogeneity … so we thought if the model predicts it correctly that is just fine." (Interview Vera van Beek, June 24, 2011)

Using geotechnical models on a scale smaller than the target systems in question changes the effects of gravity, which will lead to different behavior of soil. As a result, phenomena observed in a model may only occur in the laboratory, and are therefore not representative of the target system. Centrifuge modeling provides a way to compensate for "difficulties associated with scaling … by using a geotechnical centrifuge to increase the local equivalent gravitational field in order to balance the decrease in stresses that would otherwise result from the chosen linear scale." (Wood 2004, 269) Using a centrifuge model located on the premises of Deltares on the *Stieltjesweg*, geotechnical engineers at Deltares conducted an experiment on a 1:80 scale model of a dike, which showed how a scale model of a dike could fail due to piping. The outcome of this experiment meant a step forward in terms of validating previous small- and medium-scale experiments. More generally, centrifuge modeling can provide an opportunity to update (preliminary) theories about geotechnical phenomena in the light of unexpected results. The use of centrifuge models also has negative aspects. Paul Schaminée, Advisor Experimental Research at Deltares, who is actively involved with experiments carried out by means of the GeoCentrifuge, points out that centrifuge models are sometimes used to improve the stature of reports. Doing additional experiments on a centrifuge model is costly, but can give a report a scientific edge, even in the absence of elaborate use of the model, e.g. by using different setups, different types of soil, etc. Schaminée laments this careless use of centrifuge models, which he calls 'illustrative calculation'. (Interview Paul Schaminée, March 24, 2009)

Large-scale experiments as the pinnacle of validation

Despite the promising use of centrifuge modeling in terms of validation, geotechnical engineers did not consider it an all-encompassing solution to the aforementioned scaling issues. Any model is based on assumptions and hypothetical conditions, and therefore never neatly corresponds to the complexity and variation of its target system. To provide more elaborate means of studying piping and validating geotechnical models, geotechnical engineers have conducted experiments using full-scale[45] dikes as part of the so-called 'IJkdijk' (literally 'calibration dike') program (see figure 4.6).

Figure 4.6 An IJkdijk after an experiment in late 2009. Photo by Vera van Beek. © Deltares.

The IJkdijk experiments also provided a platform for testing and calibrating new monitoring techniques. Although the name of the project suggests there is one single IJkdijk, the project is really an area where several dikes are constructed. After each experiment, a new IJkdijk needs to be constructed on a different part of the terrain where the experiments take place. Each experiment has an impact on the properties of the soil, which may influence the outcome if subsequent experiments take place on the same location. The IJkdijk experiments provided additional insights into the onset and progress of piping. A total of four experiments related to piping were conducted, in all cases leading to dike failure, proving once and for all that piping needs to be taken seriously. According to Ulrich Förster, who leads Deltares' research into piping, this was

[45] The IJkdijk experiments were full-scale, but not necessarily representative of Dutch dikes overall, since the experiments featured a maximum creep length of 15 meters. However, many river dikes will feature much greater creep lengths of around 50 meters.

not so much questioned by the geotechnical engineers involved. However, before the experiments of the IJkdijk program, several Water Boards were not convinced piping was really an issue. (Interview Ulrich Förster, May 27, 2009) The IJkdijk program therefore had an important persuasive effect as well.

Geotechnical engineers often emphasize the uncertainties related to their research: they lament the fact that the empirical data about the soil on which structures are built is often not available, and characterize the behavior of soil as 'complex', and 'non-linear'. According to many engineers, some dike failure mechanisms remain hard to predict, computational prowess and more data about geotechnical phenomena notwithstanding. The ensemble of small-, medium- and large-scale models used by geotechnical engineers provides a way to deal with the uncertainties introduced by modeling geotechnical phenomena on different scales. Small-scale, medium-scale, and large-scale experiments all feature uncertainty. The IJkdijk experiments provide the means to validate experiments carried out on smaller scales. When IJkdijk experiments validate the outcomes of smaller-scale models, geotechnical engineers consider the latter more suitable to study geotechnical phenomena on larger scales. This reduces the necessity to conduct expensive experiments on a full scale.

An important outcome of the small- and medium-scale models in combination with the IJkdijk experiments was that existing calculation rules could be corrected. These calculation rules did not correctly predict critical head in the case of coarse sand particles, and were updated on the basis of the SBW research on piping. Another result of the IJkdijk experiments was that the engineers involved learned more about the time it takes for a dike to fail because of piping. Vera van Beek describes how retrograde erosion turned out to take much longer than expected. Small-scale models usually showed a single channel where the process of retrograde erosion proceeded quickly. In the case of large-scale models, the process of retrograde erosion could sometimes take several days. Once the pipe had fully formed, erosion increased strongly and would clog the pipe created earlier, which was not something the engineers expected. The clogging of a pipe can make the widening of a pipe a time-consuming process. As van Beek further explains: "two out of four experiments led to breaches, but the other two did not … in those cases we needed to carefully dig a channel to create a pipe which eventually did lead to a dike breach." (Interview Vera van Beek, June 24, 2011) The creation of pipes in these cases provoked erosion that eventually led to dike breaches. Van Beek found it took longer than expected for a dike to breach due to piping. The experiments showed that the process of retrograde erosion could sometimes take days, which can be a positive outcome for the safety assessments of Dutch dikes. However, van Beek also pointed out that dike breaches can occur very rapidly once retrograde erosion and the widening of the pipe have been completed, leading to sudden and violent dike breaches.

Although much progress has been made in terms of validating existing calculation rules used to assess piping-related risks, the research is not complete, nor can geotechnical engineers provide a concrete prediction when piping is understood sufficiently:

> "A risk with large-scale experiments is that you try to validate too many things, and that is not possible. So the setup has been relatively simple, as were the aims of the model validation. But you cannot validate all of the aspects of the model. Eventually you will get a critical head in the form of a number, and the only thing you can do is check whether that kind of corresponds with what we thought, and yes, on that basis you need to trust the model, but you cannot validate all aspects. That is tricky. That requires much more experiments." (Interview Vera van Beek, June 24, 2011)

Förster points out that the process of validation has been "sufficiently thorough" in terms of *Rijkswaterstaat*'s request for an updated calculation rule for future assessment rounds. However, Förster also points out that additional experiments are needed as a basis for comparing the outcomes of different model runs. Research on piping is therefore not complete:

> "The research does not rid you of the problem. You keep discovering new blind spots. The moment you have a calculation rule it may be state of the art, but that does not mean you are really at the end of the research … one experiment is no experiment, you always need to compare the results of different experiments, but it is always a question of time and money … *Rijkswaterstaat* expects us to come with a new calculation rule this year, so there comes a point where you have to say good is good enough. But uncertainties remain." (Interview Ulrich Förster, May 27, 2009)

Förster further explains that the outcome of SBW research can therefore be counterproductive in terms of reducing uncertainties, since more knowledge about piping can also lead to a larger number of dikes that turn out to be vulnerable after all. Förster does not think geotechnical phenomena can be captured once and for all in calculation rules due to the complexity of such phenomena. However, Förster does admit he believes in "progressive understanding" since the bandwidth of uncertainty is decreasing due to the validation of calculation rules. (Interview Ulrich Förster, May 27, 2009)

Han Knoeff, a geotechnical engineer at Deltares working on piping, expressed his doubts about attempts to capture piping once and for all in a calculation rule:

> "I do not believe in a calculation rule that represents reality. The phenomenon features lots of different aspects, and you can never capture those correctly. You have to provide a schematization of reality before you can start calculating, and reality is so complicated. Those sand layers can be one centimeter thick, they can be small, large, vertical, horizontal, making the soil so heterogeneous you cannot capture it in a single calculation rule." (Interview Han Knoeff, May 26, 2009)

The experiments in the laboratory provide ample evidence for Knoeff's observation that piping is a rather complex and local phenomenon, where the interactions of heterogeneous soil can make a crucial difference. In principle, vast quantities of information about soil could make a difference, but this is impossible to realize in practice. In addition, the onset and process of piping can be sudden, making even the hypothetical scenario of perfect models in combination with exhaustive data about soil problematic in terms of preventing piping altogether.

Any geotechnical model features potential difficulties related to the experimental setup. Geotechnical engineers need to confront a plethora of potential problems arising from the experimental setups they use, e.g. they need to find out what types of sand need to be used in the model cross-section, make sure the water pressures used correspond to the conditions of dikes in the Netherlands, and determine whether the Plexiglas cover exerts the right pressure on the model foundation. The dikes used in the various IJkdijk experiments may match the dimensions of 'real' dikes due to its size, but its experiments are certainly not without difficulties and potential sources of uncertainties, such as the producers of measuring devices and sensors. The IJkdijk program is seen as an 'innovative' platform for risk monitoring, and a large number of parties want to jump on the wagon. According to Ulrich Förster, companies were so eager to fill the dikes used during IJkdijk experiments with measuring devices that it came to a point where the devices could influence the experiment. Since these measuring devices are located on the border between the sand layer and the clay of the dike, they may influence the experiment. A careful balance needs to be struck between using an acceptable number of measuring devices and creating the conditions for the occurrence of piping in such a way that the experimental setup corresponds with reality as much as possible. Additional experiments were planned to provide room for the parties working with measuring devices. (Interview Ulrich Förster, May 27, 2009)

The correspondence between the outcome of the IJkdijk experiments and how piping 'really' proceeds is based on the intuition and expertise of geotechnical engineers. André Koelewijn, a geotechnical engineer working at Deltares, points out that experiments can lead to issues that cannot easily be resolved. Some of the experiments conducted as part of the IJkdijk program take longer than the number of hours of sunlight during a given day, which requires the installation of generators near the area where the IJkdijk experiments took place – a remote site in the north of the Netherlands. These generators provided power for lamps, but may also influence the experiment by generating vibrations that introduce noise in some of the data generated by measuring devices. Then again, it is not uncommon for such vibrations to occur since a ship may pass by or a truck may cross the dike 'in reality'. This makes it difficult to decide whether the vibrations of generators distort the experiment or may perhaps introduce phenomena important in real world scenarios. (Interview André Koelewijn, June 18, 2009)

Future research

Though progress has been made in terms of updating Sellmeijer's calculation rules, van Beek admits that these improvements involve "empirical corrections" of a theoretical calculation rule, which she finds,

> "still somewhat unsatisfying … we need to find the cause for [the empirical corrections]. Although we conducted experiments on multiple scales, we have some certainty that the adaptation of the model does not have to do with the experimental setup of the small-scale experiments, for example. Or at least not

> for the largest part. But … it has to be investigated since there is of course a reason for the adaption of the model, maybe 3D effects play a role or the erosion mechanism that is embedded in the model might be incorrect.” (Interview Vera van Beek, June 24, 2011)

Still, van Beek finds the adjustments to the calculation rules adequate in the context of the SBW research on piping.

The unexpected outcomes of the piping experiments have led to a number of topics for future research. First of all, future research on piping will need to assess the influence of heterogeneous soil layers in dike foundations. Heterogeneous sand layers can subdue the growth of pipes since pipes can be weak and collapse due to pressure, but erosion may also be sped up since water can flow more easily through larger sand particles. Laboratory experiments often make use of homogenous sand layers, since this enables the comparison of outcomes of different experiments. However, homogenous sand layers are not representative of actual dikes. Experiments involve an important ambiguity: on the one hand, they need to have continuity to make sure that different experiments can be compared. On the other, the tests also need to be representative of the complexity and variety of real world phenomena, and thus should explore a variety of scenarios. The challenge for experimenters in general relates to balancing continuity and representativeness (Downer 2007).

Second, experiments using small-scale models showed an important influence of the packing density of sand layers, which is determined by the pressure of top layers and soil properties. When small-scale experiments were carried out using loose packing densities of sand, the process of seepage erosion would start in the middle of the sand layer or at the water side rather than the land side of the dike (‘forward erosion’ from water to land, rather than ‘backward erosion’ from land to water, as described above). The updated calculation rules cannot account for forward erosion. In addition, the hydraulic head that provoked retrograde erosion was much lower in the case of low packing densities. This implies a critical head that is much lower in comparison with sand layers with a higher packing density. This could mean that piping may occur sooner in sand layers that feature loose packing, and that heave may occur in unexpected locations.

A third aspect of piping to be researched is the influence of time. The IJkdijk experiments revealed that critical head needs to exert pressure for long periods of time to complete the process of retrograde erosion from the land to the water side of the dike. This can be to the advantage of safety assessments, since it is more unlikely that critical head persists over long periods of time. Furthermore, the behavior of pipes over time is not fully understood – do they collapse or persevere over time?

The possibility for geotechnical engineers to do more research will depend on the availability of resources. Experiments on scale models are particularly expensive, which can make it difficult for engineers to acquire funding. For example, when Förster attempted to acquire funding for IJkdijk experiments, he noticed some hesitation on the part of *Rijkswaterstaat* and had to persuade them further to convey the high added value of such experiments. The role of the IJkdijk program as a platform for innovations can therefore aid the process of securing resources for additional research. (Interview Ulrich Förster, May 27, 2009) Other influences on resource allocation for geotechnical research will be discussed in more detail in section 4.3.

Relevant knowledge and uncertainties in geotechnical research on piping

The usage of geotechnical models described above involves a process of discovery, whereby the various uncertainties in theories about piping are engaged and reduced where possible. Through an elaborate process of using different models, existing calculation rules used to assess piping-related risks are validated and improved where necessary. This particular aspect of modeling bears close semblance to what Oreskes et al. (see the introduction to this chapter) have identified as 'model heuristics', where models are important agents in guiding further study (see the introduction to this chapter). However, geotechnical models do not only fulfill an exploratory function in the laboratory; they also acquire the status of representations of geotechnical phenomena due to their crucial role in safety assessments and dike safety policies. The use of model results in safety assessments necessitates that geotechnical modeling features some kind of deliverable: state of the art calculation rules that are considered to be reliable not only by geotechnical engineers, but also by other social groups, such as decision makers, policy makers, and stakeholders. Geotechnical models acquire epistemic currency, since one or more social groups value them as reliable means to explain and/or predict geotechnical phenomena. Sections 4.2 and 4.3 engage the concerns of decision makers, policy makers, and stakeholders in more detail, and ask how these social groups assess the reliability of geotechnical models.

Although the use of geotechnical models in research on piping is explicitly aimed at reducing uncertainties, their current use in geotechnical research revealed sources of uncertainty that may impact the outcome of geotechnical research: the difficulties encountered in the laboratory, such as the challenges of observing small-scale soil morphologies and difficulties associated with the experimental setting of geotechnical models. In addition, the issue of scaling may continue to plague the use of scale models. Displacement piping was an unexpected outcome of an experiment with scale models, but whether this is a feature of real dikes is unknown. Finally, there are aspects of piping that need to be addressed by future research, which is dependent on the allocation of resources from parties like *Rijkswaterstaat* or companies that consider projects like the IJkdijk to be worthwhile.

4.2 Flood control

In the above discussion of the IJkdijk program, large-scale geotechnical models form the pinnacle of a long chain of activities, which starts with observations and leads to the validation of calculation rules by means of full-scale experiments. Within the laboratory, geotechnical models fulfill a primarily heuristic role by virtue of being representations “useful for guiding further study but not susceptible to proof.” (Oreskes et al. 1994, 644) Outside the laboratory, simulations and models are fulfill the role of representations, which provide knowledge that serves as the input for safety assessments and flood risk management. Geotechnical modeling in the context of dike safety assessments features a slippery slope from exploration to representation. In this section, I address two aspects of dike safety policies and flood risk management in the Netherlands that cause geotechnical models to fulfill a more representational rather than exploratory function. First, I argue quantitative methods contribute to the perceived ability of geotechnical models to provide reliable explanations. I refer to these quantitative methods as ‘data-intensive’ methods, since they feature the use of large amounts of computational resources and data. The latter is made available by measuring devices, such as sensor networks and laser altimetry, which feature prominently in the IJkdijk project. Data-intensive methods are not simply at odds with the aforementioned experiential and tacit knowledge at play in the laboratory, but are not a straight-forward extension of these forms of knowledge either. Second, by virtue of being considered as reliable explanations of dike-related risks, geotechnical models can help to furnish the viability of evacuation procedures. Similarly, requirements of policy environments cause geotechnical models to function as representational rather than exploratory techniques, as will be explained in more detail in section 4.3.

From experimentation to data gathering

Geotechnical engineers working on piping at Deltares do not consider calculation rules to be indicative of a complete understanding of piping. Still, Ulrich Förster observes an increasing reliance on computational methods and the gradual abandoning of physical models:

> "As soon as there is a degree of certainty about the process, such models are supposedly no longer needed … I think you still need to look at physical models to get some kind of sense of phenomena. If you only work with computer simulations you might distance yourself too much from reality." (Interview Ulrich Förster, May 27, 2009)

According to the geotechnical engineers at Deltares, validated geotechnical models are true in a pragmatic sense, which makes them sufficiently reliable in terms of understanding and predicting piping. Although geotechnical engineers at Deltares attribute importance to tinkering in the lab, intuition, and expertise, they also believe in 'progressive understanding' (see previous chapter): at some point, the knowledge of a geotechnical issue or phenomenon is considered to be reliable, allowing the codification of knowledge in the form of a calculation rule. The validation of geotechnical models thereby enables the development of calculation rules that allow more quantitative approaches to piping, rather than the qualitative experiments in the laboratory that were discussed in the previous section.

The viability of data-intensive methods is based on the presumption of computational tractability: the ability to quantify phenomena and subsequently predict or monitor these phenomena using computational methods. However, the extent to which social actors are convinced of computational tractability depends on their technological frame (see section 3.2). Nico Pals and Bram van der Waaij of TNO argue that geotechnical modeling and data-intensive methods can be combined to create a novel approach to dike safety. Pals and van der Waaij do not propose a paradigmatic shift towards data-intensive techniques, but stress the importance of combining such techniques with geotechnical modeling. For example, data about past events can be fed into a database, which can then be consulted to predict the likely behavior of a dike in those cases where present circumstances are similar to those in the past. Pals explains as follows:

> "You do not have to understand geotechnical phenomena to be able to predict them … if you can analyze a large amount of data by means of Artificial Intelligence, you can make statements about the future without understanding the process … a dike watcher will do the very same on the basis of past experiences and common sense without having a clue about what goes on inside the dike." (Interview Nico Pals, July 30, 2009)

Pals does point out that the accuracy of measuring data remains a potential weak spot since data-intensive techniques rely heavily on data. Bram van der Waaij shares Pals' aforementioned ideas regarding prediction, and remarks that using data-intensive techniques provides an important advantage:

> "You can provide answers an expert cannot, because an expert tries to understand it and provides a well-founded answer. You could actually also say that Artificial Intelligence allows you to assist the expert in gaining an understanding of what happens." (Interview Bram van der Waaij, July 30, 2009)

Data-intensive techniques guide the attention of experts, and can point out which dikes need to be subjected to further scrutiny, e.g. by carrying out structural improvements or monitoring their status more closely. Unfortunately, Pals and van der Waaij point out, institutions and companies in the field of water management in the Netherlands can sometimes be archaic and resist innovative techniques. The past years have witnessed somewhat of a break with this trend in the form of an increasing enthusiasm for data-intensive techniques.

Calculation rules may pave the road for quantitative approaches and may shift the focus of engineers away from experimentation, and justify an emphasis on monitoring techniques that focus on data generation and management. Such data-intensive methods use models, data infrastructures that enable the processing of large amounts of data with extensive use of computational resources, and data visualization. Laser Imaging Detection And Ranging (LIDAR) is an example of such a data-intensive method that can be used to monitor dike safety. LIDAR can detect dents in the surface of dikes that can indicate damage in the structural integrity of a dike. Another example of a data-intensive technique is the use of remote sensing to detect temperature differences that can indicate the permeation of water in a dike that might be caused by damage inside the dike. Such techniques can also be used to detect damaged slope protections, which make the dike in question susceptible to damage from waves that reach the dike's outer slope. This can be caused by the right combination of high tide and powerful winds from a certain direction that can lead to overtopping. Further sources of data include the various types of measuring devices used in the IJkdijk experiments, such as temperature sensors, humidity sensors, and low-frequency microphones.[46]

Robert Hack, who lectures in soil mechanics and geotechnical engineering at the Faculty of Geo-Information Science and Earth Observation (ITC) of the University of Twente, has a rather different approach to data-intensive techniques than that of Pals and van der Waaij. Hack argues quantitative techniques should be approached with apprehension:

> "When the first numerical applications arrived around the time of my graduation, the dominant idea was that everything could be solved … we simply enter the differential equations, create sufficient nodes, and if it calculates long enough we get an answer that is completely accurate! We will know exactly what is going to happen! Well, it turned out that that is *not* correct!" (Interview Robert Hack, June 5, 2009)

Hack further explains that simulations and models allow all kinds of sophisticated calculations, but these instruments are often used without understanding the underlying processes and sufficient data to validate the model in question.[47] The complexity of soil morphology and the lack of data about soil problematize the validation of numerical

[46] Movement of soil inside a dike that can damage its structural integrity generates sound waves that can be picked up by microphones.

[47] The difference between the more descriptive method advocated by Pals and van der Waaij and Hack's more exhaustive understanding can be related to the difference between predictive and structural validity described in section 2.2. The former claim a model that predicts behavior accurately is sufficient, whereas the latter stresses the importance of a more thorough understanding of the phenomena in question. The choice between predictive and structural validity thus appears to be influenced by the technological frame of simulationists.

models. A strong reliance on such models can imply vulnerability, especially in the absence of data to validate the model: "as long as you keep that in mind that is just fine." However, when the output of a geotechnical model is used in large-scale projects, "things can go awfully wrong. Model output is often accepted as being holy without being subjected to further attention … if [model output] does not differ too much from reality, people simply carry on." (Interview Robert Hack, June 5, 2009) It is therefore crucial that the inner workings of the model are understood, Hack claims, also because the process of validation may only generate more uncertainties. Understanding how the model arrived at a particular result enables a degree of control, which can be used to critically assess model output.

Still, Hack understands how geotechnical engineers need to meet the requirements of professional environments and the political arena, which often require them to produce quantitative knowledge. Expertise is simply no longer seen as a sufficient basis for making decisions in those environments, since it is not unanimously accepted and cannot be controlled easily. The use of data-intensive techniques provides Dutch water management with an innovative edge, and may seem to enable reliable approaches to flood risk management in the eyes of policy makers. When I asked Hack how he felt about the Flood Control 2015 program (discussed in more detail below), he saw it as an important development, but also found the enthusiasm on the part of the Dutch Minister of Infrastructure and the Environment somewhat misplaced: "It was embraced by the Minister, who was jumping up and down, my experts are going to monitor the strength of our dikes from the sky! *laughs* I thought, let us see about that." (Interview Robert Hack, June 5, 2009)

Vera van Beek, whose work I discussed earlier, is also not sure to what extent monitoring techniques can be used to counter the risks posed by piping, which occurs on such a small scale that successfully monitoring dikes necessitates a dense network of measuring devices that provides frequent output. When measuring devices are too far apart, a pipe can simply disappear 'under the radar' and remain unnoticed. A further problem is that it is unclear how long it will take for a dike to fail as a result of piping. It is not possible for dike watchers to rely fully on observations of sand transport (e.g. sand boils) that characterize the process of piping, since this does not necessarily provide an indication of how long it will take for a dike to fail due to piping: retrograde erosion and widening of pipes may require days, but may also occur suddenly and violently. As van Beek explains,

> "the time it takes for a dike to fail is long and the process may appear innocent until right before the dike fails. I think that formed the opinion of the dike watchers, because they may think that every time they see a sand boil it is not going to lead to such a large chance of a dike fail." (Interview Vera van Beek, June 24, 2011)

The fact that piping takes place inside a dike makes it even more difficult for dike watchers to see in what stage the piping process is at that moment.

In conclusion, there appear to be different and not necessarily compatible commitments to the idea of computational tractability. Geotechnical engineers tend to interpret model output as a result that needs to be revised constantly in the light of new research results. In other social groups, computational tractability enables monitoring techniques that are valued as reliable, innovative, and cutting-edge. In the following description of the Flood Control 2015 project, I show how the representational role of geotechnical models further takes shape due to current trends in flood risk management in the Netherlands.

Flood Control 2015

In the context of adaptive approaches to water management and flood protection (see section 1.1), geotechnical models about dike failure mechanisms are not used exclusively to understand dike failure mechanisms, but also aim to pave the way for successful monitoring techniques and evacuations. Codified calculation rules enable the dissemination and reproduction of geotechnical knowledge, which can travel outside of the laboratory to policy contexts in the form of applications. The use of data-intensive methods further adds to the perceived credibility of such applications. In the following, I discuss the Flood Control 2015 project that aims to develop data-intensive applications for adaptive measures. Examples of such applications are data mining techniques and probabilistic modeling, but also applications aimed at decision makers, policy makers, and stakeholders, such as (interactive) data visualizations and serious games. Dutch risk governance increasingly embraces the process of translating expert knowledge to policy makers, which is expected to lead to participatory forms of flood risk management.

Flood Control 2015 is a consortium that consists of commercial companies and governmental institutions (Arcadis, Deltares, Fugro, Royal Haskoning, HKV, IBM, ITC, Stichting IJkdijk, and TNO). The consortium takes an approach to flood risk management that consists of measuring and monitoring, forecasting, and action and mitigation. Many of the activities of the consortium are devoted to translating geotechnical knowledge to operational contexts populated by decision makers, policy makers, and stakeholders. ICTs function as the backbone of applications that allows information to be distributed to the latter groups of users, who can thus be equipped with the means to monitor flood-related risks, predict flood-related scenarios, and commence evacuations when necessary. A futuristic suite of applications has been produced by the consortium that has been able to turns heads in the world of flood risk management. These applications are praised not only in terms of innovation and the use of cutting-edge technologies, but also for their ability to translate geotechnical knowledge to a public of non-experts.

On January 20, 2010, the Flood Control 2015 consortium organized a symposium that functioned as a showcase of their various projects. Throughout the symposium the free circulation of accurate information was stressed as a crucial component of successful adaptive strategies. During his keynote lecture, Luc Kohsiek, the head of the Water Board *Hollands Hoogkwartier*[48], referred to the flooding of New Orleans in 2005 to emphasize what he considered to be a crucial difference between the Netherlands and the United States: the Dutch are not very well-prepared for evacuation scenarios in comparison with the Americans. Kohsiek emphasized that the dissemination of information is of great importance during the preparation and implementation of evacuation schemes. Kohsiek pulls up a slide showing a conference room, dubbed the ‘war room’, that features (with one single exception) men, laptops, and beamers projecting maps of the Netherlands and feeds of data related to flood risk and dike safety. Such war rooms can function as a central node in networks of information that are of crucial important during a crisis, and allow Water Boards to successfully plan and execute an evacuation of a particular area. “In such situations,” Kohsiek points out, “it is quite pleasant when those present are primarily experts and not politicians.” Laughter erupts from the room. Kohsiek continues by stressing the need to bridge the gap between ‘experts’ and ‘non-experts’. A noble venture in principle, but Kohsiek’s earlier casual remark provides an immediate reminder of the issues

[48] The heads of Water Boards are known as ‘*dijkgraaf*’, which literally means dike warden. The origin of the title is clearly linked to the history of the Water Boards, which are in charge of the maintenance of flood defenses, water ways, water quality, and sewage treatment since the 13th century.

commonly associated with the creation of spaces where the perspectives of engineers collide with those of decision makers, policy makers, and stakeholders.

Kohsiek's remarks pertaining to the value of shared information reverberated throughout the day, but were certainly not embraced unconditionally. A project that bears close semblance to the 'war room' environments presented by Kohsiek is the so-called Demonstrator Flood Control Room (DFCR, see figure 4.7), an interactive user environment that features a variety of applications that can be used to analyze and visualize data from flood- and dike monitoring networks.

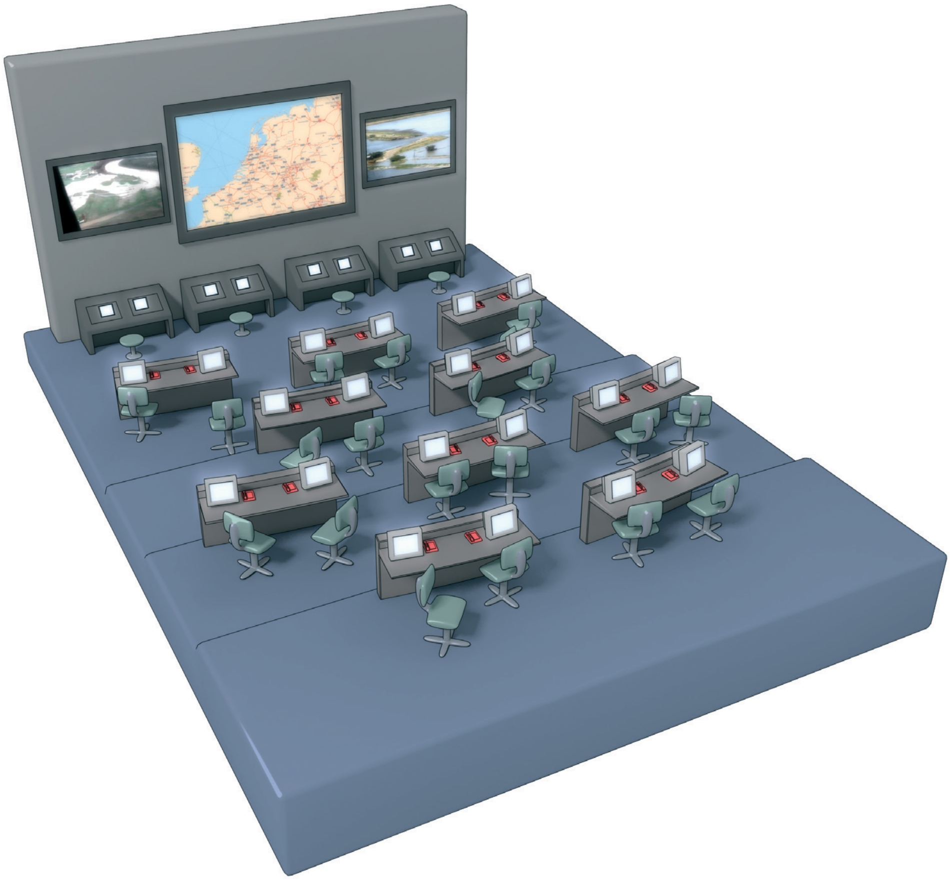

Figure 4.7 Demonstrator Flood Control Room (DFCR). © Deltares.

The DFCR functions like a central control platform in that it integrates data feeds generated by other components of the Flood Control 2015 project, including the sensor networks and remote sensing technologies discussed earlier, which allow it to present weather conditions, water levels, and the status of dikes in a particular area.

Simulations and models are an important component of the DFCR, although they may require a tremendous amount of computational resources and therefore cannot always be applied in evacuation scenarios. One solution to this issue is lowering the resolution of models, leading to faster calculation. Another solution is running models beforehand using input data that corresponds with scenarios that have a high probability, and subsequently include the output of these model runs in the DFCR. In that case, calculations are not carried out during the actual use of the DFCR, making users reliant on model output rendered before the event of an actual critical situation. An additional use of the DFCR is that it can be used as a training environment, since it can simulate different scenarios to which users need to respond.

Although participants of the symposium valued the DFCR as a platform to integrate information, its possible implementation was approached with caution. Using the DFCR as a central platform to share data among different parties might make the dissemination of data more efficient and reliable. However, the successful implementation of the DFCR depends on a process of standardization that might not be welcomed by all parties involved, since local requirements may differ from the standards accompanying the use of the DFCR. The discussion around standardization engages such practical problems, but also turns to potential dangers: what if uncertainties and assumptions creep into data that only reveal themselves when it is too late? Quantified information can travel more easily to different domains of use in principle, but does not appear to roam about freely. The solutions pertaining to the dissemination of information thus occasionally tend to emphasize technological possibilities rather than considerations related to actual applications.

A further complication related to the dissemination and application of information is that expert knowledge from engineering environments needs to be translated to fit the demands of decision makers, policy makers, and stakeholders. Applications that fit these demands need to be designed, and therefore imply both an enabling and constraining effect on the user's interactions (Akrich 1987). This requires an elaborate process of distilling large amounts of expert knowledge in such a manner that decision makers, policy makers, and stakeholders are presented with knowledge that is considered to be sufficiently detailed for the issues they face in a time of crisis. For example, one presentation elaborated on the use of websites where decision makers, policy makers, and stakeholders could access data visualizations. Rather than presenting model output in high detail, such websites aim to present information that can support the process of decision making when an evacuation is imminent or in progress. Underlying geotechnical models are effectively blackboxed, and the websites are presented as innovative and cutting-edge platforms to represent the information gathered by means of data-intensive methods.

A related example of applications used to disseminate knowledge from 'experts' to 'non-experts' is the so-called 'Levee Patroller' game (see figure 4.8), which was created by a team of software engineers at Deltares who specialize in the development of 'serious games' – computer game environments developed for educational purposes.

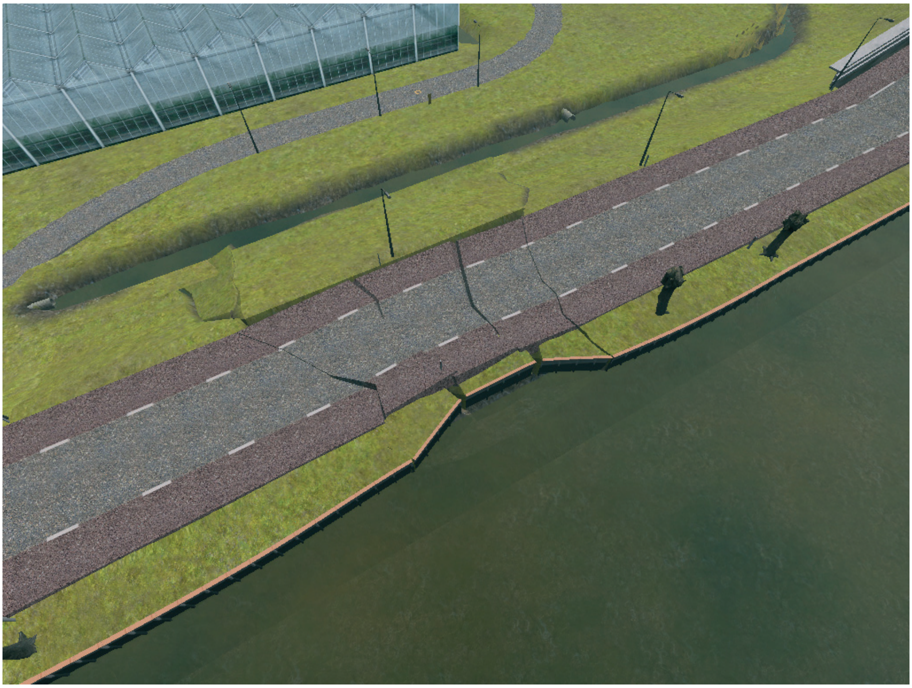

Figure 4.8 Screenshot from the game 'Levee Patroller' showing a damaged dike. © Deltares.

The Levee Patroller game is currently used to train dike watchers and also includes piping. The game deals with piping by including animations of sand boils in order to address this failure mechanism. The Levee Patroller emphasizes "procedural skills" rather than "conceptual understanding" of piping on the part of its users. (Harteveld 2011, 233) Players of the Levee Patroller game earn rewards by correctly identifying risks and subsequently reporting those risks to a water management authority.[49] This

[49] The work of Ghamari-Tabrizi shows that 'war games' such as war games do not intend to resemble reality. Rather, they are built around narratives that are based on lived experiences and expertise of military personnel, and rely on a 'demand of realism' as part of the dramatization. (Ghamari-Tabrizi 2000, 199)

may be a suitable way to make users of the Levee Patroller aware of the piping phenomenon in general. However, although sand boils indicate that piping is indeed in progress, they do not provide a clear indication of how much the process of retrograde erosion has advanced. Additionally, the onset and process of piping can be both gradual and sudden. Dike watchers may place wooden frames around the sand boil, which reduces the hydraulic head since the buildup of water inside the boards applies counter pressure to the water on the other side of the dike. This procedure is known as '*opkisten*'. In practice, the effectiveness of this method is questionable since the counter pressure it can apply may be insignificant in case of a large hydraulic head.

Other than the issues involved with standardization and dissemination, and the question how information can best be presented to an audience of decision makers, policy makers, and stakeholders, the Flood Control 2015 symposium discussed organizational challenges regarding flood risk management. During a session where participants were asked to enact an evacuation scenario, the session's organizers attempted to tackle the issues that come up during evacuations, especially in the negotiations between local authorities, such as decision makers, the police, and firefighters. One of the issues that emerged from the enactment was the question whether such negotiations should have an open and democratic character, or whether a single party or actor should rather have a mandate that allows him or her to make swift decisions. In addition, the session's participants pointed out that the behavior of citizens and decision makers can be uncertain in times of crisis. Citizens may simply not respond to the request to leave their homes, and decision makers may not be up to the task of making far-reaching and clear-cut decisions on the basis of uncertain information. The behavior of decision makers in times of crisis is further complicated by issues of political credibility: unnecessary evacuations lead to loss of face, and may compromise the value of calls for evacuation in the eyes of the general public. In sum, a decision maker will never decide purely on the basis of information about a critical scenario, which is often already uncertain itself. Finally, although the design of thorough evacuation plans and training for evacuation scenarios were seen in a positive light, the session's participants latter also stressed the importance of deviating from such plans when necessary.

Relevant knowledge and uncertainties in data-intensive methods and the Flood Control 2015 project

The use of data-intensive methods does not only open up new ways of engaging geotechnical phenomena for engineers, but also furnishes the development of 'smart' and 'innovative' applications in the form of software, which are expected to enable adaptive forms of flood risk management. Data-intensive techniques are important ways for geotechnical engineers to mobilize resources for further research. Geotechnical engineers can mobilize more resources for doing fundamental research when they also adopt strategies that align well with the Flood Control 2015 program. Thus, the work of the 'engineer-entrepreneur' can be analyzed using a front stage and back stage analogy: as much as geotechnical engineers stress the need for fundamental research, their ability to actually do that research partly depends on their ability to position themselves in the framework of innovative flood risk management.

The uncertainties related to data-intensive methods relate to the question whether quantitative methods suffice, and how quantitative research should be carried out. The process of codification effectively blackboxes geotechnical knowledge in the form of a calculation rule or computer code, which can lead to epistemic opacity (see previous chapter). This can make it more difficult for users to assess the impact of such calculation rules or computer code. Similarly, the discussion on Flood Control 2015 revealed the standardization of data and the design of applications for decision makers, policy makers, and stakeholders imply a degree of epistemic opacity. Knowledge generated by means of elaborate geotechnical models needs to be made accessible for an audience of non-specialists and fitted to the requirements of flood risk management in action. Standardized data may not be compatible with local practices and may cover up errors that only become apparent in retrospect. A different source of uncertainties became apparent during the discussion on organizational aspects of decision making in a time of crisis, which looked at the influence of the political interests of decision makers and headstrong local populations who often act according to their own ideas about risks, making their actions less amenable to control.[50]

[50] Wynne (1992, 117) mentions "indeterminacy" that results from "real open-endedness in the sense that outcomes depend on how intermediate actors will behave." The various applications related to the Flood Control 2015 program feature indeterminacy in the sense that their functioning and value in evacuation procedures will, at least in part, depend on organizational and human components.

4.3 Dike safety policies in the Netherlands

In this section I return to the policy-related aspects of dike safety policies that I briefly discussed in the introduction. As shown above, the LRT of 2006 indicated that the safety of a large percentage of Dutch dikes could not be assessed. As the LRT of 2006 points out, the correct assessment of dikes prevents a number of issues. When a dike is falsely claimed to be unsafe, unnecessary improvements may be carried out that are costly and disruptive to the environment where the dike in question is located. On the other hand, when a dike is falsely claimed to be safe, risks may be veiled and there may be an unfounded sense of safety. Finally, the inability of *Rijkswaterstaat* to assess the safety of a large percentage of Dutch dikes (as was the case in the LRTs of 2001 and 2006, see table 4.1) may cast a shadow on the image of flood risk management in the Netherlands. In addition, in those cases where an official judgment cannot be made, improvements will not be carried out since they might not be necessary in the first place. Improvements on dikes that fall into the category 'no judgment' are put aside until more thorough assessments can be made.

	1st assessment (1996-2001)	2nd assessment (2001 – 2006)
Meets the standard	40%	44%
Does not meet the standard	19%	24%
No judgment	41%	32%

Table 4.1 The outcome of the LRTs of 2001 and 2006.

'No judgment'?

As disturbing as the remarks above may sound, Frans Hamer, who directs the SBW program at Deltares, argues there are a number of misconceptions about dike safety in the Netherlands in general and the category of 'no judgment' in particular. Hamer expects that the 2011 results of SBW will probably indicate a percentage of 21% of Dutch dams and dikes as 'not up to the standards'.[51] Hamer points out the percentage of dikes in the category 'meets the standard' can decrease due to structural improvements. Hamer also explains how assessment results are likely to change due to

[51] Although a new dike safety assessment report was published in late 2011 when this book was finalized, I decided not to incorporate these insights. After all, a central tenet of this book is the idea that knowledge about risks is constructed, and needs to be studied by means of thick descriptions of technological practice. This precludes an easy insertion of new details about the Dutch dikes into the present chapter, especially since I lack empirical data to support substantial claims about how the assessments published in 2011 came into being.

research carried out in the SBW program. Such research can lead to new assessment rules that subsequently produce different outcomes of safety assessments. As a result, dikes that were considered to be 'safe' in one assessment round may be considered 'unsafe' in the next assessment round, or vice versa. Dikes in the category 'no judgment' can also move to the categories of 'meets the standard' or 'does not meet the standard' as a result of new assessment rules.

Still, Hamer predicts tendentious explanations of the categories 'does not meet the standard' and 'no judgment'. "I can almost already read the headlines", Hamer says, "one fifth of the Netherlands unsafe!" (Interview Frans Hamer, July 15, 2010) As Hamer points out, the assessments are based on criteria that apply in "extremely rare situations" and that the assessments are very thorough. Hamer stresses that the assessments are based on a likelihood of initial damage inflicted by water (erosion of the dike) and deformation of a dike. However, initial damage and deformation do not always lead to breaches, even though deformation can damage infrastructure and buildings on top of the dike. However, the large percentage of dikes in the category 'no judgment' is used to point out the Netherlands might be prone to flooding: "I know professors who say things like: 'would you get on a plane where 24% of the parts do not function correctly?' That's exaggerating of course." (Interview Frans Hamer, July 15, 2010) The difference between 'not meeting statutory requirements' and 'unsafe' are often forgotten in critical accounts of dike safety in the Netherlands. Such critiques may be clouded by a lack of awareness of how safety assessments take place, and how dikes can move from one category to another depending on the assessment rules that are used. A closer look at the categories of 'safe', 'unsafe', and 'no judgment' used in the LRT can indicate how policy environments shape knowledge about dike safety, and how policy making relates to work carried out in the laboratory and beyond that was discussed in the foregoing.

The LRT of 2006 admits that the percentage of dikes that fall into the category 'no judgment' is high, and provides different reasons for this. First, there may be a lack of data that precludes making unambiguous judgments about the safety of flood defenses. Although more data about flood defenses (e.g. their design, information about their foundations) has become available throughout the history of the periodic assessments, there is still a lack of data in a number of cases. Practical constraints are partly responsible for this lack of data. Some flood defenses are very old structures that cannot be studied without inflicting damage or substantial costs, which in some cases can make safety assessments problematic.

Second, in case an assessment body fails to provide knowledge about all failure mechanisms that need to be assessed according to the VTV, the flood defense in question is categorized under 'no judgment', even if a single failure mechanism has been left out of the assessment. Thus, this rigorous assessment criterion may veil substantial work carried out by the assessment bodies.

Third, a similarly rigorous cutoff is the date of submission for safety assessments: if an assessment body fails to provide an assessment in time it will not be included in the LRT, leading to the end result of 'no judgment'. Assessments may take a long time and may therefore run out of step with the intervals prescribed by the VTV. The amount of time required for both assessments and structural improvements has led to proposals to increase the interval of the periodic assessments.

Fourth, the VTV includes stringent requirements pertaining to the ways in which the assessments are carried out. In those cases where assessment bodies used an assessment method different from the ones prescribed by the VTV, the assessment was grouped under 'no judgment'. The issue is particularly pressing with regard to the different categories of flood defenses identified by the Flood Defenses Act, which distinguishes three different categories of flood defenses based on location and function. Category A and B together form the primary flood defenses. Category A flood defenses are dikes, dunes, and hydraulic structures that provide direct protection against the sea and the great rivers. Category B flood defenses connect category A and category C defenses, e.g. the *Afsluitdijk* and *Maeslantkering*. Finally, category C defenses, or secondary flood defenses, provide indirect protection against inundation. These flood defenses provide a secondary line of defense against floods in case other flood defenses fail, for example by preventing a flood from inundating neighboring land. Examples of category C flood defenses are those alongside the *Noordzeekanaal*.

The issue flood defenses that fall in the category 'no judgment' is particularly pressing in the case of category C defenses: whereas the WTI and HR regulate the assessment of category A and B defenses, there are no assessment regulations or hydraulic boundary conditions for category C defenses. During the assessment of category C defenses between 2001 and 2006, assessment were asked bodies to compare the physical conditions of category C defenses in 1996 with those same physical conditions in 2001. In those cases where these physical conditions had not changed between 1996 and 2001, the safety attributed to those defenses was sufficient, or 'meets the standard'. Many assessment bodies found this method unsatisfactory, and decided to use assessment criteria tailored to their own needs, e.g. by determining their own hydraulic boundary conditions. Fifty-five percent of the category C flood defenses were tested using these locally developed assessment criteria. The Ministry of Infrastructure and the Environment eventually decided the assessments based on local initiatives could not deviate from the national standard, and would therefore be valued as 'no judgment' in the LRT of 2006. As a response to the lack of coherence in assessment methods of the assessments carried out between 2001 and 2006, the Ministry of Infrastructure and the Environment decided to implement a national template for safety assessments, for example through the use of GIS applications.

The assessment round that took place between 2006 and 2011 contained stronger incentives for assessment bodies to carry out thorough assessments. Safety assessments are in some cases difficult (due to the morphology of soil and a lack of data) and expensive. The Ministry of Infrastructure and the Environment is responsible for financing structural improvements to flood defenses. The new WTI prescribes that assessment bodies may only reach the outcome 'does not meet the standard' after carrying out a so-called 'advanced' assessment, as opposed to the less detailed 'simple' and 'detailed' assessments: "if you really want to show a flood defense does not meet the standard, you need to be able to show you did everything in your power to reach your conclusion." (Interview Remco Schrijver, August 11, 2011) Han Vrijling, Professor in Probabilistic Design and Hydraulic Structures at the TUD, pointed out to me this can also have less advantageous effects:

> "If you manage to keep a flood defense in the category 'no judgment' and *Rijkswaterstaat* produces a new boundary condition or calculation rule … it might be included in the [*Hoogwaterbeschermingsprogramma*]. So in that case it is in your interest, as a Water Board, to keep it in that category, because there might be a chance that someone else will pay for renovations." (Interview Han Vrijling, November 29, 2010)

In the discussion above I have unsettled the category of 'no judgment' by situating the production of knowledge about dike-related risks in the context of policy-related requirements. The category of 'no judgment' does not simply indicate a lack of knowledge, but needs to be understood against regulations imposed by the Ministry of Infrastructure and the Environment. Frans Hamer's previous remarks are in that sense justified: there is more than meets the eye, and 'no judgment' does not simply indicate imminent flooding or a lack of attention to dike safety, though it may be interpreted as a sign of neglect (e.g. in the eyes of the general public). The category 'no judgment' is shaped by the policy environments in which dike assessments are situated. Similarly, the three possible responses to floods due to dike breaches that will be discussed below, research, adaptive measures, and preventive measures, need to be understood against policy-related aspects of safety assessments.

Research: rules of calculation

Structural improvements to flood defenses notwithstanding, the LRT of 2006 concluded hat 24% of the Dutch dikes did not meet the criteria imposed by the assessments - an increase compared with 19% of the Dutch dikes that did not meet the standard in the LRT of 2001 (see table 4.1). The percentage of dikes that did meet the standard increased from 40% in 2001 to 44% in 2006. Although it is tempting to draw conclusions from these percentages, it is problematic to compare the outcomes of different assessment periods since both the HR and WTI evolve over time. For example, the first assessment round (1996-2001) mainly looked at dike height, whereas the second assessment round (2001-2006) also included the stability of flood defenses. Changes in the HR and WTI shed a different light on the LRT reports: rather than straightforward indications of a development of safety, the percentages mentioned in each LRT report are first and foremost indicative of safety assessments as they were practiced in the time of that particular assessment round. Remco Schrijver confirms the discrepancies between different assessment rounds, and points out that piping has only been assessed thoroughly in the third assessment round. In addition, Schrijver stresses different assessment rounds cannot be compared easily:

> "In the second assessment round, the amount of no judgment was more than 30% and in the third assessment round it will be considerably lower. You can reach two conclusions on that basis … the assessment instruments have improved or the Water Boards have made a greater effort, or a combination of the two. So it is difficult to compare assessment rounds because … the

> assessment rules you use for the assessments are not the same." (Interview Remco Schrijver, August 11, 2011)

Due to the research activities carried out in the SBW program during each assessment round, vested ideas about dike failure mechanisms may change, leading to new ideas about critical conditions and how dikes may fail. The use of different methods makes it difficult to compare the outcomes of the different assessment rounds. The outcomes of the LRTs of 2001 and that of 2006 should therefore also be understood against developing insights in geotechnical engineering that shape the outcomes of the assessment rounds. Through negotiations with assessment bodies and provincial authorities, the Ministry of Infrastructure and the Environment ultimately decides what research is carried out in the SBW program. What is more, the Ministry also sets the priorities for the research program based on the extent to which research proposals for each SBW cycle can contribute to safety assessments. As I mentioned in section 4.1, engineers need to negotiate with government bodies in order to acquire the necessary resources to do further research.

However, as much as policy making fulfills the important function of allocating resources for geotechnical engineering, it is also bound to dynamics other than purely research-related interests. The production of knowledge about geotechnical phenomena and the subsequent inclusion of this knowledge in dike safety policies should be seen in a landscape of interests, which are not always compatible. As Remco Schrijver points out, there is a lot of discussion in flood risk management in the Netherlands, since the HWBP is

> "getting out of hand, financially … Research has led to a better insight into piping and an improved calculation rule … So much is uncertain right now that it was decided that starting a new assessment round was not very useful." (Interview Remco Schrijver, August 11, 2011)

Schrijver's comments also reveal more about the interests underlying the inclusion of new knowledge in the WTI. Research on piping led to the development of a new calculation rule, which will be included in a new version of the VTV and HR. However, it is not certain when this new knowledge will be applied in safety assessments of flood defenses:

> "The question right now is how do you deal with that new knowledge? Because in the meantime dikes are being improved, also dikes that were assessed as susceptible to piping, should you use the old assessment rule for those dikes or the new one? If you use the new one, it is quite a blood-letting for the state, but if you do not do it, such a flood defense will be assessed as unsafe in a couple of years … we never expected that research into piping would yield such new insights … On the one hand we are very busy doing more research … but on the other hand you also create an uncomfortable situation because you can generate insights, about piping for instance, of which you could not predict the impact five years ago … but the reverse is also possible." (Interview Remco Schrijver, August 11, 2011)

One possible response to threats indicated by safety assessments entails further research on assessment methods and criteria. In that case, making 'unsafe' dikes 'safe' does not so much involve carrying out structural improvements, but rather adjusting the criteria on the basis of which flood defenses are judged to be unsafe. DG Water has the authority to determine which calculation rules will be taken up in the WTI. The Dutch government also faces financial difficulties. An evaluation of the HWBP (see introduction) stressed the need for additional investment of 900 million euros (Taskforce Hoogwaterbescherming 2010).

Adaptive measures

Flood risk management in the Netherlands appears to have somewhat abandoned the more classical, preventive approach of keeping the water out at all costs, and adopted a model with a stronger focus on adaptive measures and strategies, such as evacuation (cf. Bijker 2007a). Thus, flood risk management may help to minimize the consequences of dike breaches and subsequent floods (Pols et al. 2007). Van der Most et al. (2010) point to two important causes for the increasing attention for adaptive measures: the sudden collapse of a peat dike due to drought in 2003 in *Wilnis*, the Netherlands, and the 2005 flooding of New Orleans in the United States. Both events are repeatedly referred to by engineers and policy makers working in the field of water management, and have apparently led to the firm establishment of the idea that unexpected and critical events can and will happen.

The Flood Control 2015 project is emblematic of the shift to a more adaptive style of flood risk management, since it contains many projects that display a strong commitment to evacuation and the idea of 'preparedness', which "proposes a mode of ordering the future that embraces uncertainty and 'imagines the unimaginable' rather than 'taming' dangerous irruptions through statistical probabilities." (Aradau 2010, 3) Forms of flood risk management that emphasize preparedness imply a new form of citizenship, in which commitments to self-sufficiency shift the responsibility of responding to critical events to citizens of technological cultures.

During a debate on January 28, 2011 hosted by the Royal Institute of Engineers (KIVI NIRIA), the advantages and disadvantages of both apative and preventive approaches to flood risk management were discussed extensively. The adaptive approach to flood risk management was represented by a team of experts led by Jeroen Aerts, Professor of Water, Risk and Insurance at the Institute for Environmental Studies of VU University in Amsterdam. During his opening lecture, Aerts admitted knowledge about dikes and engineering-related solutions to floods is far more extensive than current studies of adaptive water management. A logical conclusion from this observation is that it makes sense to prioritize research on dike improvements, but Aerts also asks how this choice can be justified if so little is known about adaptive strategies to begin with. Further research on adaptive strategies may make them more feasible as a response to the risks posed by flooding.

A team led by Han Vrijling that defended preventive approaches opposed Aerts' team. Vrijling pointed out that ongoing debates merely put the Netherlands at risk since they divert attention from what is really important: dike maintenance and structural improvements. The basis of flood risk management should be the notion of acceptable risk, where economic considerations are the main focus.[52] Based on this idea of acceptable risk, Vrijling argues, it might not even be feasible to prepare inhabitants of areas prone to flooding with the means to take adaptive measures. According to Vrijling, the adaptive water management is flawed since it interprets flood risk management as a chain of different measures, ranging from prevention to adaptive measures. This chain can only be as strong as its weakest link, so it is preferable to make sure the dikes will hold in the first place. Thus, costly adaptive strategies, such as the compartmentalization of land to create buffer zones for floods, or installing an organization that monitors safety and regulates evacuations can be avoided. Vrijling

[52] See also Vrijling et al. 1998.

laments the differentiation between politicians and engineers, and receives support from the audience. "There are two possible scenarios", a member from the audience vehemently argues, "either a disaster will take place, or we get a minister of Infrastructure and the Environment with a technical background, like Lely."

Preventive measures

Assessment procedures may be subjected to independent evaluations carried out by external reviewing committees, such as the ENW that was mentioned in the introduction. When both VNK1 and VNK2 (see section 4.1) indicated a severe risk of dike failure as a result of piping in the Netherlands, DG Water assigned the ENW with the task to write an independent review of the instruments used to assess piping-related risks. Although VNK2 included an improved assessment method for piping, it yielded a picture of piping-related risks that was as alarming as the outcome of VNK1.

The report was aimed at ensuring piping posed a serious risk to the safety of the Netherlands, which reverberates in the report's title: 'Piping: realiteit of rekenfout?' ('Piping: reality or calculation error?', Vrijling et al. 2010). The ENW concluded piping indeed posed a danger to the Netherlands and was by no means an artifact of calculations used. What turned out to be especially troubling was that existing assessment methods do not take into account the so-called 'length-effect': several dike failure mechanisms, including piping, macrostability (the sliding of inner or outer slopes) and instability of slope protection, are strongly influenced by the properties of the soil that vary along the length of a dike. The heterogeneity of soil, lack of data thereof, and the complexity of soil morphologies further complicate the study of the length-effect. When taking into account the length-effect for a dike ring rather than a dike segment, the ENW concluded that the risk of dike failure due to piping could be five to ten times higher than expected, making a response in the short term an absolute necessity. In addition to the absence of the length-effect in the assessment methods, the ENW concluded that the calculation methods used in the Netherlands are less strict in comparison to calculation methods used elsewhere. Whereas other countries make sure seepage erosion cannot occur at all, design rules and assessment methods in the Netherlands are aimed at preventing pipes, but not seepage erosion per se. What is more, the VNK assessments used the calculation methods developed by Bligh under the assumption that these would yield a more severe risk of piping than Sellmeijer's method (both Bligh's and Sellmeijer's approach to piping are discussed in section 4.1). However, the opposite turned out to be the case, leading to the requirement of longer creep lengths to counter piping than indicated in VNK1 and VNK2. Current assessment methods assume Bligh's calculation method to be more stringent, potentially leading to severe underestimations of piping-related risks.

Based on these findings, the ENW discusses three possible responses: waiting for the results of future research, adaptive measures[53], and preventive measures. The first of these is ruled out as a suitable response. The ENW does not expect additional research to yield a considerably better picture. Additional research to eliminate uncertainties in models or gather more data about soil are only relevant in case they yield an assessment of piping-related risks that is less troubling. The ENW argues this outcome is unlikely, especially since safety assessments in the Netherlands use relatively lenient assessment criteria, as argued earlier (Vrijling et al. 2010, 25). Postponing necessary measures will only put the Netherlands at risk. Adaptive measures can be taken in case there is immediate danger of a dike breach due to piping, for example by the previously described method of *opkisten*, or commencing evacuation procedures. However, the reliability of procedures for doing so has not been proven, and adaptive measures often leave much room for error in the form of insufficiently detailed procedures or human error.

The ENW is strongly in favor of preventive measures in the form of piping banks, creep screens, or other structural improvements, which are known to provide a solution to piping, but also other failure mechanisms. The total costs for preventive measures over 1100 kilometers (about one third of the total length of primary flood defenses) are estimated at €1.4 billion (Ibid. p. 30). Additional data on soil underlying flood defenses susceptible to piping may lower this amount. By comparison, the ENW estimates the immediate financial risk of a severe flood at €2 billion (Ibid.). The after-effects of a severe flood can increase that amount (e.g. further loss of life, disruption of economic activities, damage to the reputation of the Netherlands, etc.), but are difficult to indicate in quantitative terms.

The ENW report discussed above can be aligned with some of the concerns raised by Vrijling, whose work featured briefly in the foregoing discussion on adaptive measures. In line with the previous concerns expressed with the ENW, Vrijling suggests a more technocratic approach that focuses on structural improvements of Dutch dikes.

[53] The ENW report mentions 'repressive' rather than 'adaptive' measures. However, it is clear they wish to question the value of adaptive forms of flood risk management.

The costs for such an operation are often grossly overestimated. (Vrijling 2008, 716) The debate between proponents of structural improvements and proponents of evacuation methods has not settled and certainly does not involve a neat separation between these two styles of flood risk management. The two teams that debated the preventive and adaptive approaches to flood risk management during the KIVI NIRIA debate discussed above expressed that their approaches were not mutually exclusive. However, the current discussions about how to implement the large amount of new knowledge about failure mechanisms generated in the latest assessment round and how safety measures can be covered financially show that the dust has yet to settle.

Vrijling thinks the emphasis on ecological concerns and adaptive measures are indicative of what he calls a "weakened mentality." (Interview Han Vrijling, November 29, 2010) Vrijling adds that the perceived value of innovative projects such as the development of tulip-shaped islands off the Dutch coast is a sign of the times. Rather than conforming to the "environmental hype" that currently forms a dominant way of thinking in Dutch water management, Vrijling argues that dikes "just need to meet the statutory requirements." (Interview Han Vrijling, November 29, 2010) However, providing a counterweight to this 'weakened mentality' can be extremely difficult. Vrijling laments the lack of knowledge about quantitative methods he often encounters. The development of innovative methods, such as serious games, as adaptive measures against floods is based on a refusal to adopt a more engineering-oriented agenda:

> "I think you need to know it yourself. Well. Before you can make decisions, you cannot simply say well I am lazy, and I exaggerate a little bit, I am too lazy for this world, all those thick course books of engineers, I am not going to look at those, I do not feel like that. Make me a serious game so I can decide." (Interview Han Vrijling, November 29, 2010)

Vrijling does not think additional research into failure mechanisms will paint a brighter picture of the current state of the flood defenses in the Netherlands:

> "There is a tension between what we think we know and the experiences of our ancestors, who said, once water starts coming over the dike you better hide! And now we conduct experiments in regulated conditions, and those turn out pretty well. But make no mistake, it is a long dike and there only needs to be a

> vulnerable spot on one single location … that is also the problem with piping … even though the dike can be strong on average." (Interview Han Vrijling, November 29, 2010)

Relevant knowledge and uncertainties in Dutch dike safety policies

As Disco and van den Ende have argued, "engineering is about shaping not only matter but also the social networks in which matter is molded." (2003, 503) As the foregoing discussion on geotechnical research and external evaluations has made clear, the 'social networks' discussed by Disco and van den Ende can be quite stubborn. The repertoire of responses to dike-related risks consists of doing more research on dike failure mechanisms, evaluating existing assessment methods, the development of evacuation procedures, or proposing preventive measures. This range of possibilities harbors conflicting interests that meet in today's arena of flood risk management, where vested interests may problematize the uptake of knowledge on failure mechanisms, preventive measures, or adaptive measures that can have disruptive effects.

Dike safety is then not given, but rather constructed by means of a recurring process of assessment-related practices, and the adherence to financial and socio-political requirements. In this process of reconstructing knowledge about risks, simulations and models fulfill a crucial role in producing knowledge relevant to the social actors described above, i.e. as a way to respond to the political loss of face due to flood defenses that fall in the category 'no judgment', balancing the need for re-assessments and structural improvements, or as the means to develop evacuation procedures as viable responses to dike breaches and flood risks. Knowledge produced by means of geotechnical models that help to determine the safety of flood defenses has to 'settle' in the form of knowledge that meets the requirements of policy environments. In addition, policy-related interests also shape the uptake of geotechnical knowledge: knowledge about dike failure mechanisms may be available, but not applied for various reasons. Policy making may hereby become a source of uncertainty: discussions between proponents of research, adaptive measures, and preventive measures feature diverse (and often conflicting) values that shape the production of knowledge about geotechnical phenomena, and as a result also co-determine to what extent uncertainties about such phenomena are affirmed and studied.

Conclusion: resilience or adaptive capacity?

In this chapter I showed how dike safety assessments in the Netherlands feature a range of practices, which produce knowledge in ways relevant to the various social groups involved. First, geotechnical engineers at Deltares are committed to an elaborate process of research to reduce uncertainties of geotechnical models, and develop state of the art calculation rules that can be used in safety assessments. As shown in the previous chapter on hydraulic engineering, the value of geotechnical models is based on practical success, which emphasizes relevance rather than truth. In practice, relevance may be confused with truth, particularly outside of the laboratory where different commitments to dike safety assessments come into play. Second, the use of data-intensive methods indicates a commitment to more quantitative approaches, and the development of software aimed at an audience of 'non-experts'. Thus, geotechnical engineering becomes embedded in a context aimed at the development of 'innovative' technologies. Commitments to preparedness form an important incentive for the development of these technologies. Third and finally, the discussion of policy-related aspects of dike safety assessments in the Netherlands showed how policy making shapes the context in which the practice of geotechnical modeling takes place. Commitments to research, adaptive measures, and preventive measures indicate how the repertoire of dike safety assessments and flood risk management in the Netherlands is taking shape, and show that geotechnical models do not function as free-floating knowledge instruments.

Geotechnical engineering and knowledge about dike failure mechanisms increasingly need to be not only epistemically robust (e.g. by producing more accurate calculation rules), but also need to meet requirements related to 'social robustness'[54] (e.g. by being perceived as innovative or by being aligned with commitments to preparedness). For geotechnical engineers, this can imply they need to become engineer-entrepreneurs: they need to produce knowledge that is considered to be relevant by their peer community of geotechnical engineers, but also need to answer to the interest of a broader audience of decision makers, policy makers, and stakeholders. Whereas 'front stage' presentations of geotechnical models stress their representative capacities, 'back stage' presentations stress their exploratory capacities. According to geotechnical engineers, simulations and models can only present the problem at hand in a more or

[54] Gibbons et al. (1994) and Nowotny (2003) develop the idea of social robustness, which they place in a broader context of an increasing demand for scientific knowledge that can be valorized and can yield practical benefits.

less satisfactory manner that may provide insights. As such, geotechnical models are only representative of geotechnical phenomena to a limited extent. Outside of the laboratory, geotechnical models tend to be seen more as reliable representations of geotechnical phenomena.

By looking more closely at the different aspects of geotechnical engineering both within and outside of the laboratory, I showed how the use of geotechnical models implies various uncertainties. Engineers may speak of a 'profound' form of uncertainty that is due to a lack of measurement data and the complexity of soil morphologies. The challenges involving experimentation (ensuring comparability between experiments, dealing with unexpected outcomes, and scaling) form additional sources of uncertainty. The use of geotechnical models outside of the laboratory may introduce challenges in the form of epistemic opacity and contexts of use. Finally, the outcomes of discussions about commitments to research, adaptive measures, and preventive measures cannot be predicted, but do shape knowledge production and the extent to which uncertainties are the topic of further study.

In the foregoing, I adopted Gross' definition of uncertainty as "a situation in which, given current knowledge, there are multiple possible future outcomes." (Gross 2010, 3) Uncertainty can put technological cultures at risk: attempts to develop definitive calculation rules, implement 'innovative' technologies for geotechnical modeling and flood risk management, and develop policies related to dike safety can be 'unsettled' by uncertainty. The three aspects of dike safety assessments discussed above (geotechnical modeling in the laboratory, data-intensive methods and software development in the context of flood risk management, and policy making in the context of dike safety assessments) all harbor uncertainty in the form of multiple possible future outcomes. For example, a calculation rule may turn out to be in need of improvement, an application developed for flood risk management may yield unexpected outcomes or be used in an unforeseen manner, and policymakers may not adopt the insights produced by research into dike failure mechanisms. Uncertainty can therefore put technological cultures at risk: the methods chosen to cope with various risks may be out of step with the multiple possible future outcomes that various uncertainties may imply.

Uncertainty can be used to describe 'knowledge gaps' or blind spots, for example in dike safety assessments. However, uncertainty does not simply entail a lack of knowledge, but is a by-product of simulation practice that cannot (and probably should not) be ruled out. From the perspective of geotechnical engineers presented in section 4.1, claims to certain knowledge need to be approached with apprehension: the reliability of geotechnical models does not imply an objective truth, and calculation rules are always 'merely' an indication of knowledge produced thus far. These calculation rules have acquired credibility through successful application, but that does not mean geotechnical models are complete or 'finished'. Commitments to adaptive and preventive measures rather than research show that the challenge of dike safety in the Netherlands is particularly pressing according to those involved, and may also imply dismissive attitudes to approaches that are not considered to be feasible solutions. The history of the Netherlands is replete with successful interventions on the part of engineers, providing engineering with a stature that can be difficult to criticize.

The various practices related to dike safety assessments can be interpreted as a process of alignment with dike-related vulnerabilities where different agendas collide. Technological, institutional, and socio-political aspects of geotechnical modeling constitute an apparatus by means of which the safety of flood defenses in the Netherlands is both assessed and addressed. This process of alignment can proceed through 'collective experimentation' (Stengers 2009), which requires that the social groups involved learn to understand their responsibility for and commitment to approaching the world based on what is relevant to each of them. Studies of uncertainty can contribute to the process of collective experimentation. As Donald MacKenzie (1999) argues, uncertainties are approached and valued differently by various social groups. As became clear, geotechnical modeling may not only contribute to the reduction of uncertainties, but can also lead to awareness of uncertainties. Although the outcome of simulation practice may be disruptive and cause difficulties in the realm of policy making, it is of vital importance to affirm the value of uncertainties, since these can lead to new insights about dike failure mechanisms. Whether geotechnical models are able to fulfill this role partly depends on the interests of the various social groups involved with dike safety assessments.

Although uncertainties can put technological cultures at risk, they also form a source of knowledge about risks. The extent to which uncertainty puts technological cultures at risk is determined by a tension between resilience (defined here in the narrow sense as 'stubbornness') and adaptive capacity. As I pointed out in section 1.2, resilience is not necessarily opposed to vulnerability: if resilience defines the capacity of a system to return to its initial state, while the initial state was the source of the system's vulnerability, resilience appears to be something to avoid. Vulnerability should rather be contrasted with adaptive capacity. This implies a need to remain vulnerable in the sense of susceptibility to new knowledge and insights that uncertainties may entail. The settling of knowledge in the form of calculation rules, software, or policies that are considered to be epistemically and/or socially robust is what may put technological cultures at risk. Settled knowledge can imply a diminished ability to evaluate the pros and cons of various approaches to uncertainties, and preclude the adoption of uncertainties as a source of knowledge about risks. Simulation practice and its technological, institutional, and socio-political aspects can steer technological cultures in the direction of either resilience or adaptive capacity.

5. Designing communication: politics and practices of participatory water quality governance

Introduction

On October 23 2000, the European Union (EU) adopted the *Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy*, also known as the *Water Framework Directive* (WFD). The objective of the WFD is to "establish a framework for the protection of inland surface waters, transitional waters, coastal waters and groundwater". (European Union 2000, 5) This means the WFD aims to prevent the deterioration of aquatic ecosystems, protect or enhance the status of aquatic ecosystems, promote sustainable water use, and enhance protection and improvement of the aquatic environment. These objectives can be achieved "through specific measures for the progressive reduction of discharges, emissions and losses of priority substances and the cessation or phasing-out of discharges, emissions and losses of the priority hazardous substances." (Ibid.) Through a strict schedule, the WFD obliges Member States of the EU to meet its requirements: after translating the WFD into the legislative frameworks of the Member States of the EU, responsible authorities needed to be identified, and River Basin Management Plans (RBMPs) needed to be drafted by 2009 at the latest. These RBMPs record the status of bodies of water within a river basin district, formulate the measures needed to meet the objectives prescribed by the WFD, and act as a reporting mechanism to the EU and the general public. The objectives of the WFD need to be met by 2015. If additional measures appear to be necessary, an extension can be provided in order to meet the objectives by 2027 at the very latest.

In this chapter, I study the so-called 'WFD Explorer': a model for water quality governance that was developed to help stakeholders, employees of the Water Boards, and policy makers[55] draft RBMPs. The model provides its users with an assessment of the ecological status of bodies of water, as well as the costs and impact of measures that

[55] In this chapter I repeatedly refer to stakeholders, employees of the Water Boards, and policy makers, who together form the (intended) audience of the WFD Explorer. By stakeholders, I mean a more general group of social actors who might be affected by WFD-related measures, such as farmers and citizens. By employees of the Water Boards, I refer to decision makers and civil servants who do not have extensive knowledge of phenomena related to water quality. Although many ecologists and biologists work at Water Boards, I chose to refer to them as ecologists and biologists to emphasize their diverging positions towards the WFD Explorer in comparison with their 'non-expert' colleagues. Finally, by policy makers, I refer to national-level policy makers, e.g. policy makers working at the *Waterdienst* and other parts of *Rijkswaterstaat*.

can be prescribed in order to meet the requirements of the WFD. I interpret the development of the WFD Explorer as an attempt to facilitate participatory water quality governance. Article 14 of the WFD displays a commitment to 'active involvement', which I refer to as 'participation' in this chapter: "[m]ember States shall encourage the active involvement of all interested parties in the implementation of this Directive, in particular in the production, review, and updating of the River Basin Management Plans." (Ibid. p. 16) This is not a strict requirement of the WFD, but is seen as a best practice (European Commission 2008). Providing interested parties (such as stakeholders, employees of the Water Boards, and policy makers) with the means to influence the outcome of RBMPs meets one of the 'Aarhus Rights', which were formed during the 'Aarhus Convention' ('The Convention on Access to Information, Public Participation in Decision Making and Access to Justice in Environmental Matters', Aarhus (Denmark) June 25, 1998).

Although 'active involvement' is not defined explicitly in the WFD, the term does recur in the WFD in general terms in order to attribute an active rather than a reactive role to interested parties (Mostert et al. 2009, 11). The WFD stresses that interested parties can and should be involved in water quality governance by providing them with information, which should lead to active participation in the form of shared decision making. The underlying rationale is that active involvement meets the legal requirements of the WFD, improves decision making by attuning governance to the concerns of those involved, and increases the willingness of these parties to accept and implement policies thus developed (Mostert et al. 2009, 35). More generally, participation is expected to enable forms of governance that

> "complement representative democracy, improve transparency and accountability of government, reduce the distance between government and citizens, increase responsiveness of the state and allow individuals to protect their rights without having to institute lengthy and costly legal proceedings … promote active citizenship and empower citizens." (Ibid. p. 36)

The WFD Explorer should be understood in the context of the aforementioned commitment to participation: it was intended as a platform for participatory water quality governance that provided stakeholders, employees of the Water Boards, and policy makers in the Netherlands with the means to collaboratively explore and understand relationships between objectives prescribed by the WFD, the range of possible (sets of) measures, and the impact of those measures. In addition, the WFD Explorer was supposed to enable participatory water quality governance by disclosing 'expert' knowledge[56] to stakeholders, employees of the Water Boards, and policy makers. Thus, the WFD Explorer could act as a decision support system, or DSS, a term first coined by Gorry and Scott-Morton (1971). Turban defines a DSS as "an interactive, flexible, and adaptable [computer-based information system], specially developed for supporting the solution of a non-structured management problem for improved decision making. It utilizes data, provides easy user interface, and it allows for the decision maker's own insights." (1995, 84)

In practice, the intended use of the WFD Explorer did not work out as its developers intended. Disagreements among developers, ecologists and biologists, and users responsible for implementing the WFD Explorer in their organizations led to issues around trust and expertise, which precluded the WFD Explorer from reaching its intended audience. The model failed to gain the trust of some of its users who lamented its lack of adaptability and transparency, and as a result did not implement it. In addition, differences between 'expert' users and 'non-expert' users turned out to be difficult to bridge. The obduracy of these differences between users does not bode well for the developers' attempts to bridge the agendas of different user groups. As a result, these different user groups may continue to approach water quality governance from their own perspective, which inhibits the potential of participation to establish shared goals.

From the perspective of constructivist technology studies, the observation that technologies did not reach their intended audience is not so much a case of technological 'failure', but rather a moment of slippage where diverging interpretations and commitments can be identified and studied symmetrically (Pinch & Bijker 1984; Bijker 1995a; Wyatt 2008). Rather than treating the fact that the first version of the WFD Explorer did not reach its intended audience as a moment of failure, I discuss its development and reception in order to study the commitments and ideals underlying the commitment to participatory water quality governance. More generally, participatory forms of water governance are a rising trend in water management in the Netherlands.

[56] The difference between 'experts' and 'non-experts' or 'expert knowledge' and 'lay knowledge' is not given in advance, but rather enacted through practices of knowledge production that establish hierarchies between social groups, which can subsequently be characterized as 'experts' or 'non-experts'. This chapter and section 6.4 further elaborate on the need to study how claims to expertise are established or even reinforced by various practices.

Contextualizing participation

DSSs in various forms are in popular demand in water management in the Netherlands (e.g. van Schijndel 2006; Hoeven et al. 2009; Valkering et al. 2009). The general conception is that DSSs contribute to the political legitimacy of decision making and policy making due to their supposed accessibility and transparency. For example, the WFD Explorer was expected to enhance not only the efficiency of water quality governance, but also increase its transparency. As I showed in the previous chapter, the use of technologies that include 'non-experts' (e.g. stakeholders, decision makers, and policy makers) plays an important role in legitimating political agendas. In the context of the implementation of the WFD in the EU, participation furnishes a politically legitimate move aimed at putting environmental goals on the political agenda. The rhetoric of participation revolves around the idea that including various forms of knowledge from a multitude of parties ensures environmental concerns are met. However, participation may entail different roles for the social actors involved: some social actors get their knowledge included in governance, others only get the opportunity to engage governance in a manner pre-determined by other social actors and/or technologies (see section 3.3 on the Maptable), and social actors may differ in terms of authority in decision making and policy making. In this chapter, experts play a largely facilitating role by providing an instrument of governance, the WFD Explorer. Values about the form and content of participatory governance reverberate through such instruments of governance, which are an instrumentalization of political goals. Van der Arend et al. (2010) provide a critical perspective on the challenges related to the implementation of the WFD and making sure the concerns of various social actors are met. However, they have little attention for the development and use of instruments of governance that I take as a starting point in this chapter. In sum, I use the case of the WFD Explorer to stress the need to study not only the process of participation, but also the technologies that enable it (or aim to do so).

A standardized approach to environmental issues is crucial to the success of implementing the WFD, since it makes environmental politics manageable. This implies that a precondition of the WFD Explorer is that the various perspectives of actors involved with the implementation of the WFD need to be molded into a stable model for participatory governance. However, as the history of the WFD Explorer shows, questions about what knowledge and what actors needed to be included did not settle. Priorities and responsibilities were structured around expertise, there were differences concerning the data that experts considered to be relevant for water quality governance, and hierarchies between relevant social groups, such as developers, ecologists, and the model's intended users, turned out to be rather persistent and re-enacted during the development of the WFD Explorer. When such conflicts are encapsulated in the form of a stable instrument of governance, this instrument may end up depoliticizing disagreements about water quality by taking the real conflict out of the process of implementing the WFD, while still establishing forms of water quality governance that may become hegemonic. Hence, articulating how political goals were instrumentalized in the case of the WFD Explorer forms an underlying thread of this chapter.

Recent work in STS on technical democracies (e.g. Callon et al. 2009; Gross 2010; see also section 6.4) argues for the importance of inclusive politics that encompasses a multitude of knowledge and actors. For example, Callon et al. stress the value of so-called 'hybrid forums', which they define as follows:

> "Forums because they are *open* spaces where groups *can come together* to discuss technical options involving the collective, hybrid because the groups involved and the spokespersons claiming to represent them are heterogeneous, including experts, politicians, technicians, and laypersons who consider themselves involved … [hybrid forums] are an appropriate response to the increasing uncertainties engendered by the technosciences – a response based on collective experimentation and learning." (Callon et al. 2009, 18, my emphasis)[57]

When technical democracies commit themselves to setting up hybrid forums, they shift from a delegative to a dialogic model in which citizens take part in technical democracy. By expanding the political vocabulary, sharing knowledge, intertwining 'expert' knowledge with 'non-expert' knowledge, and affirming multiplicity, the dialogic model of technical democracy is inclusive in terms of knowledge and publics: it expands the range of issues and citizens involved with technical democracy.

However, studies of technical democracies from the perspective of STS also point out difficulties that may arise in attempts to establish inclusive forms of politics:

[57] As Isabelle Stengers argues, "Modern experimental science was 'technoscience' from the beginning, aimed not at understanding the world but at achieving mastery over it. The idea of technology as an "application of science" is, then, deeply misleading as it would ignore the fundamental homogeneity of "techno" and "science", so-called applications being the very point of scientific knowledge." (Stengers 2010, 16)

knowledge relevant to certain actors may be brushed away as irrelevant, and actors may be excluded from debates. The emphasis on participation in the case of the WFD may appear to deliver an inclusive form of politics, but the risk is that the ability of models to furnish participatory forms of governance might be seen in an overly optimistic light. Different social groups may pursue participatory forms of modeling with the intent to design inclusive spaces, which may seem a recipe to involve different kinds of knowledge and different kinds of actors, but the reality of the WFD Explorer is not always very inclusive. An unconditional belief in the inclusive potential of participatory governance may furnish a 'model democracy' (as in a model husband or model wife) that is presumably vibrant, but on closer look politically stale and may imply vulnerability: when knowledge and actors are not included in participatory governance, the latter merely re-enacts existing and hegemonic approaches to the problem at hand. In the absence of a more inclusive perspective, technological cultures may be put at risk. This does not mean I want to deliver an antithetic approach to simulation practice. Simulations and models do have important beneficial effects on water quality governance, but their broader institutional and socio-political function as knowledge instruments needs to be considered as well in order to avoid a celebratory account of participatory water quality governance.

Research questions and chapter overview

In the light of these observations, the main questions of this chapter then are the following: why did the WFD Explorer fail to reach its intended audience, and to what extent can the issues underlying this failure be overcome in order to establish more inclusive forms of water quality governance? In answering these questions, I study different stages in the history of the development of the WFD Explorer by looking at the discussions pertaining to its design, and the various ways in which developers and intended users responded to each other's ideas and actions. The perspectives of developers at Deltares and their ways of solving the issues that emerged around the WFD Explorer will occupy the center stage, though the concerns of a number of prospective users will be discussed as well. Thus, this chapter brings into focus the issues that arose during the history of the WFD Explorer, which shaped its content and eventually prevented it from reaching its intended audience.

Section 5.1 contains an overview of the motives underlying the development of the WFD Explorer, its intended audience, and it design. The section is based on various internal reports of meetings, interviews, and will also refer to other studies of the WFD Explorer (e.g. Mostert et al. 2009; Junier 2010). Taken together, these sources produce an overview of the events that transpired before the aforementioned 'failure' of the WFD Explorer. Since I visited the field after the WFD Explore failed to reach its intended audience, I wanted to use the aforementioned sources to produce an overview the values underlying its design. As I show in more detail, adapting the content of the WFD Explorer to local requirements implied difficulties that form a pretext for the issues of trust and expertise discussed in subsequent sections of this chapter, attempts of the developers to involve users in the process of designing the WFD Explorer notwithstanding. In section 5.2 I study reasons why the WFD Explorer failed to be trusted by its users, which was due to the fact that its design and uncertainties in its output were insufficiently transparent according to end users, but also due to the influence of users who were skeptical of the materialization of knowledge that the WFD Explorer implied. In section 5.3 I study issues related to expertise. Users did not always think it was possible for the model to cross disciplinary boundaries and institutional thresholds, which may turn out to be persistent obstacles in the development of technologies for participatory governance more generally. Section 5.4 focuses on the development of a second version of the WFD Explorer, and shows how its developers responded to the issues raised in sections 5.1, 5.2, and 5.3. The new version of the WFD Explorer takes a different take on participation, and emphasizes further scientific exploration with participatory governance as a possible outcome. In the conclusion, I generalize my findings and discuss forms of participatory governance where simulation practice plays an important facilitating role more generally.

5.1 From prototype to implementation: meeting local requirements

In May 2004, the first steps to develop a model for participatory water quality governance in the context of the WFD were taken by RIZA (*Rijksintituut voor Integraal Zoetwaterbeheer en Afvalwaterbehandeling*, National Institute for Integrated Fresh Water Management, a department of *Rijkswaterstaat* that later partly merged with Deltares), Delft Hydraulics (see section 1.3), and Alterra (a research institute that is part of the University of Wageningen). These three parties applied for a grant at *Leven met Water* (Living with Water, a national funding program that stimulates research related to water management). In September 2004, the development of the 'Policy Tool for WFD' commenced, which was later renamed to 'WFD Explorer'. In addition to the aforementioned parties, TUD, Royal Haskoning, and *Witteveen & Bos* and later also Arcadis (an engineering company), and University of Ghent took responsibility of parts of the development. All of these institutions provided funding for the project. The idea of the WFD Explorer was not entirely new: those involved with the development of the WFD Explorer saw the so-called Planning Kit (a DSS similar to the WFD Explorer, though aimed more at hydrological issues, see van Schijndel 2006) as a successful predecessor, and praised its ability to make complex information accessible for a 'lay audience'.

Why was the WFD Explorer built?

The myriad of problems, measures, and the desire to make complex issues tangible for stakeholders, employees of the Water Boards, and policy makers forms a similarity between the Planning Kit and the WFD Explorer. The ecological quality of bodies of water is determined by a number of factors: the runoff and emissions of natural and toxic substances, chemical processes (decay of substances and adsorption), physical processes (sedimentation and resuspension), biological processes (bacteria, algae), hydrology (flow and water level), morphology (sediment, shape of river banks), meteorology (temperature and radiation), water management (discharge and intake of water), and other anthropogenic factors (such as fishing, harvesting, and dredging). All these aspects of water quality need to be taken into account when studying the cause and possible solutions for ecological issues: water-related diseases can be met by implementing sanitation systems that remove diseases such as cyanobacteria; oxygen depletion can be countered by waste water treatment plants that help to restore natural treatment capacities; eutrophication (an abundance of nutrients leading to the growth of algae, which may damage the biodiversity of a system) can be solved through manure policies and the removal of nutrients by waste water treatment plants; loss of natural habitats can be met by restoration of flow regimes; toxic substances can be countered by regulations and removing polluted sediments; over-exploitation can be solved by integrated resource management; and finally climate change requires adaptation and transitions in energy consumption.

The diversity of ecological phenomena, water quality-related issues, and the plenitude of measures that can be taken to improve water quality point to an important motivation behind the development of the WFD Explorer from the perspective of national-level policy makers. The WFD Explorer could play a role in standardizing decision making related to water quality. By 'materializing' the knowledge of specialists in the form of a shared and standardized instrument, the WFD Explorer created uniformity in the design of programs of measures, making policy making more consistent in the varied landscape of water quality-related policy making in the Netherlands: there are 25 Water Boards, who (as will become clear later) may wish to pursue their own agendas with regard to water quality governance.

In addition, the use of the WFD Explorer enabled an important degree of standardization that would be helpful in terms of the focus of the WFD on Europe rather than individual countries. By using a shared and standardized set of procedures and terminology, the regional water authorities would make the process of implementing measures more efficient and transparent in the eyes of the European Union. More generally, the WFD creates organizational challenges and issues pertaining to decision making and policy making that European Member States need to address. Mostert et al. (2009, 16) describe these challenges and issues. First, the WFD requires not only extensive public participation, but also other forms of cooperation, e.g. across policy sectors (such as nature protection and agriculture), institutional levels, and national boundaries. Second, the current organization of water quality governance is often ill equipped to meet the aforementioned requirements of participation and cooperation, which require Member States to organize water quality governance differently. Third, the implementation of the WFD requires the acquisition and distribution of information about the status of bodies of water and the impact of measures. As I show in more detail below, this information is often not available or contested. Fourth and finally, the implementation of the WFD features uncertainties, such as uncertainty about the impact of measures and the objectives that can be met by the 2015 deadline. There is also political and legal uncertainty pertaining to the uptake of the WFD by the European Court of Justice and legal bodies of the various Member States.

From the perspective of developers, the WFD Explorer is mainly interpreted as an instrument that will assist in the exploration of the vast ecological landscape of WFD-related issues and measures. In order to allow users to determine the ecological status of bodies of water and understand the relationships between measures, their effects, and the costs of measures, the developers wanted to develop an instrument that would assist users in drafting RBMPs. The WFD Explorer was developed in order to facilitate interactive negotiations between stakeholders, employees of the Water Boards, policy makers, and ecologists. This meant the WFD Explorer had to fulfill certain demands related to interaction (see section 3.3): it was supposed to provide an estimate rather than highly detailed overview of possible measures and their effects. Low detail analyses and rough schematizations led to low computational requirements, which allowed users to quickly and interactively explore scenarios of possible measures, and thereby select those measures which are most likely to have beneficial effects. This was especially important since the developers of the WFD Explorer envisioned that the model would be used mostly during meetings and negotiations where there would be little time to wait for a model to produce its output. This also meant that visualizations were seen as a necessary aspect of the WFD Explorer.[58] In sum, the emphasis of the WFD Explorer was not so much on ecologically erudite representations, but more on enabling discussion. The developers stressed that it could be necessary to augment the use of the WFD Explorer with other modeling software to study measures and their potential effects in more detail, for example to determine exactly when and where certain measures should be implemented. This already implies a certain interpretation of future users of the WFD Explorer, who were expected to use the model in a certain well-structured manner.

The design of the WFD Explorer

The first version of the WFD Explorer consists of a calculation core and knowledge database containing calculation rules related to water quality. These two components are largely standardized, though users familiar with the design of the model may change some parameter values. A structured database is an additional third component of the WFD Explorer, in which employees of the Water Boards can enter area-specific information. This third component determines boundaries and properties of the particular area addressed by the WFD Explorer, and thus adjusts it to the characteristics of that area.

Figure 5.1 shows the user interface of the WFD Explorer. A menu at the top of the screen allows users to open or save representations of bodies of water that were made using the WFD Explorer. Users may export WFD Explorer files to a generic database format or print the representation in question. Views of the input data, characteristics, measures, results, and maps related to the water body in question are also available. Users may switch to English, edit the formatting of reports created using the

[58] Studies of visual culture attempt to show how visualizations are themselves subject to socio-political influences, which shape the form and content of visual information and the perception of social actors. Moody et al. (2013) evaluate the use of visualizations in policy making and place visual information in its political context.

WFD Explorer, and view a help file. The map screen is the main component of the WFD Explorer and displays the chemical and ecological properties of bodies of water. The WFD prescribes the use of the Ecological Quality Ratio (EQR), a method of indicating the ecological status of a particular area, where an EQR of 0 indicates a dead system and 1 indicates a healthy and diverse ecosystem. A color scheme based on the EQR is used in the WFD Explorer to display the status of bodies of water and the predicted effects of measures. A 'bad' EQR is represented in red, an 'unsatisfactory' EQR in orange, a 'mediocre' EQR in yellow, a 'good' EQR in green, and an 'excellent' EQR in dark blue. Users may choose potential measures from a list, and choose a water body where they would like to implement these measures. The model can also represent different spatial scales. Users can study whether the measures they chose can improve the EQR of various bodies of water, and receive an indication of the costs of the measure(s) in question. Finally, the bottom of the screen shows a preview of a report based on the analysis users made with the WFD Explorer.

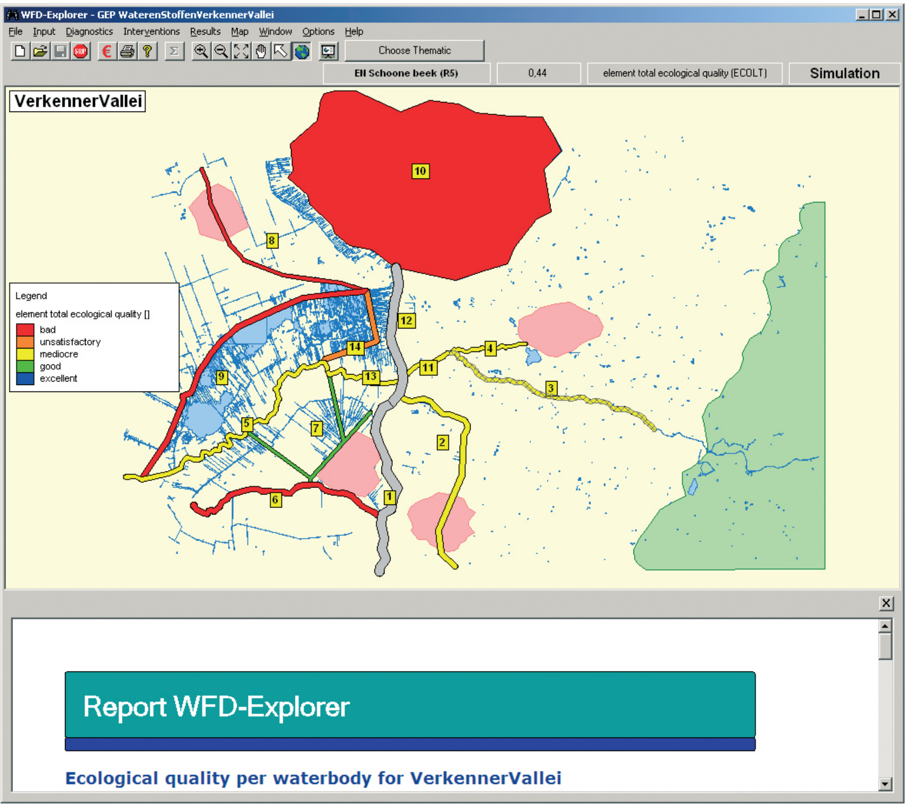

Figure 5.1 Screenshot of the WFD Explorer showing the non-existing '*VerkennerVallei*' (Explorer Valley).

Incorporating user demands

The developers attempted to meet the demands of their intended user base as well as possible during the early stages of the development of the WFD Explorer. Meetings were organized to discuss user requirements the instrument needed to fulfill in order to assist the drafting of RBMPs. Despite the relatively open structure of the development, the organizations involved had a degree of authority. Each of these institutions took care of a particular aspect of the WFD Explorer that had been allocated to them. The input of these specialists was not always discussed, and in some cases the input of specialists was based on personal experiences and expertise, rather than negotiations or unanimously accepted scientific knowledge. The developers were aware that some knowledge that was supposed to be included in the WFD Explorer was simply not available yet (Lagacé et al. 2008). These gaps in ecological knowledge were important known unknowns in determining the current state of ecosystems and the relationship between measures and effects. Despite the fact that these gaps were acknowledged, assumptions and design decisions based on personal expertise were included in the model's design. However, later proposals to do more research addressed these gaps more substantially.

At the end of 2006, the development of the WFD Explorer shifted from a more exploratory stage to a process of implementation. At the beginning of 2007, the grant from *Leven met Water* had expired. The Directorate-General for Water Affairs (DG Water, see the introduction to chapter 4) and STOWA now provided funding for continuing the development of the WFD Explorer. The initial, more experimental phase had ended, and further developing the model required an approach that included user support and regular updates. The members of the consortium established a steering group that included representatives of the various Water Boards and the institutes involved with the development of the WFD Explorer. They also formed a user group to ensure the demands of the end-user were met. Various meetings between the users group and developers were organized in order to exchange ideas for improvements and share experiences, though some users also had direct and more informal contact with some of the developers. In addition, the developers made sure end users were involved by visiting Water Boards, and tried to make the outside world aware of the WFD Explorer, e.g. by presenting their work at various meetings and workshops.

Extensive negotiations and high expectations

The development of the WFD Explorer involved a relatively open process of negotiation between a large and varied group of users. However, this open form of development eventually created difficulties as well. For example, not all negotiations led to a successful inclusion of additional knowledge and an extended public of peers and/or users. On the basis of peer reviews, several knowledge rules were rejected and omitted from subsequent versions of the WFD Explorer. The fact that the WFD Explorer contained blind spots and knowledge gaps was recognized. However, many ecologists and biologists did not contribute to the development of the WFD Explorer, since they did not think simulations and models could be used to study ecological phenomena. (Interview Joost Icke, March 27, 2009) One of the employees of STOWA mobilized his professional network in an attempt to involve more ecologists and biologists. This extended the size of the group of actors involved in the development of the WFD Explorer, but many biologists and ecologists remained skeptical of the WFD Explorer and simulation practice more generally. In addition, STOWA organized an evaluation by TAUW, an independent European consulting and engineering company that was not involved with the development of the WFD Explorer. According to this evaluation, knowledge rules related to chemical processes appeared to work well, while the quality of other knowledge rules ranged from moderate to good. The relatively open structure of the development and various peer reviews notwithstanding, many end-users working at the various Water Boards could no longer contribute to the content of the WFD Explorer. Although many users were invited to give feedback on the instrument, not all of their ideas could be included in the design of the WFD Explorer, which was in the process of being finalized.

Another issue that arose due to the open development of the WFD Explorer was that its perceived value demanded a lot from its developers. Now that the local knowledge of experts of the Water Boards was included in the WFD Explorer, more and more issues were added to the list of requirements. The developers became more ambitious, even though some prospective users were still struggling to keep up with the developments around the WFD Explorer. At the same time, the developers saw the high level of ambition as a necessary prerequisite for the success of the WFD Explorer, and felt they needed to raise the bar to interest potential users. Meanwhile, national-level policy makers and members of the funding agencies, who saw the WFD Explorer as a tool that would provide a much-needed contribution to the process of drafting RBMPs, advertised the WFD Explorer as the main tool for the implementation of the WFD. This further increased the projected value of the WFD Explorer in the political arena, and thereby also increased the responsibility of the developers and exerted more stress on them. (Interview Joost Icke, March 27, 2009) The stakes were high indeed.

User responses to the first version of the WFD Explorer

Due to the contributions of users and the value attributed to the WFD Explorer, its developers did not have sufficient time and resources to incorporate all of the changes suggested by the users and meet the new standard of quality for which they were partly responsible themselves. At the end of March 2007, a first version of the WFD Explorer was released, although updates that fixed bugs or improved knowledge rules followed soon after. Reeze and Vlieger (2009, 20ff.) describe the difficulties that ensued. The increased involvement of users through peer reviews and the resulting revisions and updates created an abundance of versions. Whereas some users complained about the degree of standardization in water quality governance inflicted by the WFD Explorer, others lamented the lack of a clear direction in the whole process. In addition, users experienced complications due to the many updates of the WFD Explorer. These ranged from conflicting results in the output of different versions of the WFD Explorer that led users to question the reliability of the model and its design, difficulties in changing the input values to attune the WFD Explorer to the region that fell under their responsibility, and a user interface that many experienced as confusing. The plethora of versions of the WFD Explorer did not allow its users to gain an overview of the pros and cons of the various versions. When the developers attempted to counter this criticism by making the model more transparent, including new functionalities, and improving the reliability of model output, the model became slower and more difficult to use. At this point, the model was already becoming less appropriate for use by stakeholders, employees of the Water Boards, and policy makers.

Presentations of early versions of the WFD were generally hailed with enthusiasm. Joost Icke, who was at that time Project Leader of the WFD Explorer, recalls a presentation to the Water Boards he gave in 2006. Icke remembers "striking a chord". (Interview Joost Icke, December 2, 2010). During and after that first presentation, various members of the Water Boards expressed the desire to work with the WFD Explorer. There was an apparent need for a tool that could be used internally to analyze issues related to water quality and thereby provoke discussions, but also externally for communication with stakeholders, employees of other Water Boards, and policy makers. During the process of making the WFD Explorer suitable for studying phenomena on a more local scale, the early adopters who had enthusiastically hailed the WFD Explorer had moved to the background. User meetings were now dominated by what Joost Icke described as "model builders", employees of the Water Boards responsible for implementing the WFD Explorer and customizing it to meet the requirements of the area for which they were responsible (Interview Joost Icke, December 2, 2010). This user group turned out to be more concerned with the actual implementation of the WFD Explorer, and was more critical than the enthusiastic group of early adopters.

Some Water Boards refrained from using the WFD Explorer altogether since they were already using similar tools for the purpose of water quality modeling. Like other available models, the WFD Explorer provided an overview of chemical and ecological aspects of water quality. Its added value was its ability to integrate knowledge from hydrodynamics, chemistry, and biology in the context of the implementation of the WFD, and provide an interactive and rough overview of the effects of measures related to the WFD. Still, other models provided similar functionalities: Alterra developed a model to assess the impact of WFD-related measures on agriculture, and PBL (*Planbureau voor de Leefomgeving*, Netherlands Environmental Assessment Agency) developed the so-called Waterplanner, a model that focuses on the ecological status of surface waters, which focuses on concentrations of nutrients. Despite this competition, about three quarters of the Water Boards did start using the WFD Explorer.

Using the WFD Explorer rather than models that were already in place did mean that Water Boards usually had to rebuild a model of their area in the WFD Explorer. Since the Water Boards saw the WFD Explorer as the main instrument to draft RBMPs, they wanted to achieve more detailed representations of ecosystems. Due to the lower resolution of models built using the WFD Explorer, Water Boards interpreted this as a decrease in model quality. The level of detail of the model was adequate for the rough, national, and systemic approach of *Rijkswaterstaat*. However, to study phenomena on a local level, the Water Boards usually had to complement the output of the WFD Explorer with additional output from other models.

Meeting user demands(?)

Despite the persistent attempts of the developers to meet the requirements of their users, the latter did not have the possibility to influence the instrument until it was too late. The team of developers wanted to get the WFD Explorer done in time, and focused on delivering the instrument to its fragmented audience, part of which was eagerly awaiting the WFD Explorer, while another part remained skeptical. During the implementation phase, the developers devoted more attention to user demands, such as on-site assistance. These commitments notwithstanding, the users did not trust the WFD Explorer. The updates never fully encompassed the requirements of the users, and users felt there was insufficient time to experiment with the model, for example to review the results of different versions. In the following section I elaborate more substantially on why the users of the WFD Explorer arrived at these conclusions.

5.2 Building trust: transparency and model skepticism

After the process of designing and implementing the WFD Explorer described in 5.1, the ability of end-users to shape the released version of the WFD Explorer and its subsequent updates was limited. Despite the open structure of the development, knowledge rules were blackboxed and based on decisions made by the relatively independent team of developers. What is more, it turned out to be difficult for users to use the model in the way they intended to in their day-to-day use. Changing input values, importing existing data sets into the model, and the process of testing and calibrating the model was for many too time-consuming in a context where RBMPs needed to be drafted quickly.

Lack of transparency

The users of the WFD Explorer who were at this point responsible for adapting the model to the specificities of the area under their responsibility (who Joost Icke described as ‘model builders’) were familiar with modeling phenomena related to water quality. As discussed in chapters 3 and 4, simulationists usually deal with models reflexively and rarely take the output of a model literally, especially since a model can sometimes yield strange or unexpected results. Though the first release of the WFD Explorer delivered outcomes that were seen as “strange and inexplicable” (Reeze & Vlieger 2009, 20), this was not a complete surprise to those involved. The quality of knowledge rules related to chemical processes was generally considered to be good, and remains one of the stronger points according to the users of the WFD Explorer (Reeze & Vlieger 2009, 8-16). However, as indicated above, many ecological knowledge rules were based on estimations and assumptions, were still in development, and were largely aimed at providing rough overviews of systems on a relatively large scale. This precluded some users of the WFD Explorer from taking the output of the model seriously. However, what really raised suspicion on their part was the epistemic opacity (see chapter 3) of the WFD Explorer. Although the documentation of the WFD Explorer is explicit about the uncertainties in the model's design, the user interface does not provide information about uncertainties. Outcomes are displayed as exact values rather than estimates within a certain bandwidth of uncertainty. In addition, users had difficulties in tracing the source of the errors in output of the WFD Explorer. Users acknowledged the lack of knowledge that made the development of formal approaches to water quality and ecosystems difficult, and did not blame the developers for being unable to solve this issue. What they did lament was that the opacity of the design of the WFD Explorer prevented them from tracing the sources of errors and uncertainties in the output of the model.

Regarding this lack of transparency, Piet van Iersel, a chemist working on integrated water management at the Water Board *Brabantse Delta* in Breda, The Netherlands, remarks that the value and exactitude of the model depend on its controllability: "the reliability is dependent on your insight into model data and calculations … if you cannot understand the model in a straightforward manner you might as well throw it out." (Interview Piet van Iersel, June 12, 2009) Van Iersel experienced the repercussions of using the WFD Explorer when studying the *Donge*, a brook near Tilburg, the Netherlands. Van Iersel's thorough knowledge of the *Donge's* myriad of different types of bodies of water and ecological phenomena differs profoundly from its relatively rough representation in the WFD Explorer. "It is quite different when you are outside. And that is the problem with these kind of model systems, reality is different from theory." (Interview Piet van Iersel, June 12, 2009)

In the case of many bodies of water like the *Donge*, using the WFD Explorer implies omissions, in this particular case phenomena related to the migration of fish. The WFD Explorer represents the *Donge* as a single, homogenous water body, potentially leading to the assumption that it is a brook like any other. A current problem with the *Donge* is that it does not allow fish to migrate due to obstructions in the form of culverts (underground pipes), watersheds, and dams. Sandra Junier, a PhD candidate working on the role of expertise in policy making, worked with van Iersel and visited the *Donge* together with him. According to Junier, the problem of fish migration in the case of the *Donge* is not addressed sufficiently due to the more systemic approach of the developers of the WFD Explorer:

> "*It is just a very complicated issue* […] the purpose of such a model is to help you with these things, but since there are so many factors *it is just very difficult* to get the specificities right. That is why I think that from the perspective of the developers, that they prefer to work on a system level, and do not want to solve the puzzle of the best location of a fish ladder, whereas that is the problem the Water Board faces." (Interview Sandra Junier, June 4, 2009, emphasis added)

When obstructions to fish migration remain invisible in the representation of the *Donge* in the WFD Explorer, the model omits this particular issue for users who do know the local system.[59]

Local phenomena and contextual knowledge are not deliberately excluded from the WFD Explorer, but they do not form an immediate starting point for its developers. The latter's systemic approach implies the development of the WFD Explorer start from a national context, which can later be adapted to meet local requirements. Many ecologists have expressed their concern about this method, and simply refused to work with the WFD Explorer since they could not identify with its approach to ecological phenomena. (Interview Joost Icke, March 27, 2009) As I make clear below, this is an objection shared by many ecologists, though there are also ecologists who object less vehemently to the use of simulations and models to study ecosystems.

Model skepticism

As much as the multitude of approaches, perspectives, and opinions on the part of the Water Boards may hinder the implementation of the WFD on a national level, forcing them to approach water quality-related issues in a homogenous way that applies to the entire Netherlands provokes criticism. Take for example the potential danger of a lack of resolution in models, which is a well-documented issue in studies of simulations and

[59] Silva et al. 2004 (quoted in Mostert et al. 2009, 45) conclude that the aforementioned Planning Kit does not include certain measures, such as dike heightening, due to an orientation in spatial planning in the so-called 'Room for the River' program that focused on enhancing flood safety while also prioritizing the quality of the Dutch landscape. Thus, the Planning Kit influenced the process of participation in a manner not directly visible to its users, and thereby featured a degree of epistemic opacity. See also section 3.3.

models in the humanities and social sciences, particularly for questions related to climate change and the danger of exclusion that an inappropriate level of details will entail (e.g. Gramelsberger 2004). In the case of the WFD Explorer, bodies of water are represented in the form of nodes (see figure 5.1). The effects of measures are calculated in terms of the interactions between these different nodes. The latter are placed at points that the developers or the experts that attuned the WFD Explorer to local specificities consider to be representative of the bodies of water in question. The nodes imply a simplification of local specificities and ecological variety, which can be glossed over in a low-resolution representation (see also the discussion on schematization in section 2.2).

Van Iersel and Junier, but also users of the WFD Explorer stress that the WFD Explorer 'tainted' or at least influenced the representation of ecosystems. In some cases, the representations produced by means of the WFD Explorer need to be supplemented by contextual knowledge and bottom-up approaches. The systematic approach dictated by the WFD may study the Netherlands on a national level, and may thereby preclude actors from studying ecological issues on a local level, which is what ecologists and biologists who remain skeptical of simulation practice usually consider the most appropriate level of analysis. Furthermore, the uniformity of analyzing phenomena on a national level may stifle innovation and sufficiently detailed analysis on the part of the Water Boards. Some users of the WFD Explorer even questioned the need for a shared instrument aimed at drafting RBMPs. Since obstacles to healthy ecosystems are often known and the set of possible measures is often limited in size, there might not be a large demand for quantitative method that opens up a multitude of scenarios. As a result, some users of the WFD Explorer were not interested in exploring new measures at all, but rather in looking at the effects of measures currently being implemented (Reeze and Vlieger 2009, 15).

However, the objections of these more skeptical users also border on stronger epistemological claims about the extent to which ecosystems can be modeled at all. These more critical users do not just claim that knowledge of ecosystems is based on highly contextual knowledge related to a particular area, which precludes making strong claims 'across the board'. In addition, model skeptics emphasize the recalcitrance of ecological phenomena by using terms such as 'complex', and portraying ecological knowledge as 'uncertain' due to the many interacting processes. According to skeptical ecologists and biologists, there simply is not enough knowledge about phenomena related to water quality, making water quality modeling a highly complex and uncertain enterprise: it takes a while before the effects of measures become apparent, restoring an ecosystem may require more than simply eliminating the conditions that have led to its demise, and there may be factors that contribute to a healthy ecological status that are simply unknown. As mentioned in section 5.1, water quality modeling features hydrological, chemical, ecological, and meteorological processes that make it an interdisciplinary field of research that calls for an integrative approach. Although he does not radically oppose the WFD Explorer, Piet van Iersel explains the concern of some of his colleagues as follows:

> "There are 3,000 species of butterflies in the Netherlands, wasps, insects, and those are all related to each other! … So you can imagine the difficulties in modeling an ecosystem, even if it is just a puddle or an aquarium, you are already in trouble." (Interview Piet van Iersel, June 12, 2009)

Water quality modeling may be identified as a 'complex' and 'uncertain' enterprise that demands a contextual approach. However, water quality governance requires disclosing 'expert' knowledge to stakeholders, employees of the Water Boards, and policy makers by means of a more systemic and standardized approach: "[t]he WFD is a complex and far-reaching directive. *It is essential that all the competent authorities and public organizations working towards its implementation have a common approach*." (European Commission 2008, emphasis added) For policy makers on the national level, the WFD Explorer needs to provide a standardized way of drafting RBMPs. As shown in more detail above, developing such a standardized and systemic approach to water quality monitoring is highly controversial among some ecologists, but certainly not all. Van Iersel is in some ways still quite positive towards the WFD Explorer and its ability to deliver tentative predictions: "[t]here is no option other than developing a good system that allows calculations … if you do not have a model you cannot predict. We cannot look into the future." (Interview Piet van Iersel, June 12, 2009)

During my encounters with ecologists and biologists at Deltares, I noticed that standardized approaches to modeling ecological phenomena are certainly not critiqued unanimously. For example, Hans Los, an ecologist and algae bloom expert working at Deltares, repeatedly referred to physics as an example of a field where a shared set of concepts and methods is beneficial. Los takes a rather pragmatic approach to the matter:

> "Look, in the case of physics Newton's laws do not appear to be completely right, but they suffice to solve 99.9% of the problems … in those cases you do not need to know that Einstein approached things differently using his theory of general relativity." (Interview Hans Los, May 6, 2009)

Simon Groot, a water quality system analyst who is a member of the project team of the WFD Explorer, makes a similar point: "[the model] might not be valid in terms of that particular species of fish that swims around somewhere, but it does describe the bulk of the system." (Interview Simon Groot, April 29, 2009) Los admits that biology and ecology feature many "differences" that cannot be approached in a straightforward homogenous manner:

> "If I explain to a biologist that I took a certain approach which led me to propose certain conclusions, he will mention that a particular observation he made cannot corroborate my findings. That is really the default answer of ecologists … it is as if they look for differences rather than similarities." (Interview Hans Los, May 6, 2009)

According to Los, looking for such similarities is especially important since many geopolitical issues feature a strong ecological component. Los refers to his personal history by mentioning the predictions of the Club of Rome that at the time provoked commitment to political issues on his part. One should not look exclusively at the accuracy of the predictions of the Club of Rome: "what is important is that they led people to take action." (Interview Hans Los, May 6, 2009) Similarly, Victor van den Berg, a policy advisor working at the Water Board *Brabantse Delta*, stressed the value of standardized approaches since they force "ecologists to make their knowledge and ideas exchangeable and transparent, implying a *more objective* approach." (Interview Victor van den Berg, May 19, 2009, emphasis added)

Erwin Meijers, who is currently in charge of the development of the WFD Explorer, also refers to the potential disadvantages of a persistent emphasis on the multiplicity, complexity, and uncertainty emphasized by many ecologists:

> "There is a tendency for [models] to become more complex, making them more difficult to understand, we throw more at these models, making their output

> more difficult to understand … I would not mind performing calculations on a more detailed scale, but then I would also like to see a handy aggregated version of the model's output. Otherwise you simply lose track." (Interview Erwin Meijers, June 18, 2009)

According to Meijers, the advantage of the WFD Explorer in comparison to other, more detailed models, is that it provokes the user to truly think about his or her assumptions. Meijers describes himself as a proponent of complex models, but more simplistic models provoke users to think about how they are modeling systems. What is more, such simplistic models may give a rough representation of complex phenomena, but that does not make their design superficial. Meijers stresses the amount of work that went into the calculations included in the WFD Explorer, not to mention the fact that simplifications were necessary for the WFD Explorer to function in policy contexts.

The agendas of both developers and national-level policy makers appear to meet at this point, since both stress the value of standardized approaches to water quality in the form of systemic, top-down approaches. For national-level policy makers, an important advantage is that developing a tool like the WFD Explorer can facilitate consensus between the various parties involved in implementing the WFD. The various Water Boards in the Netherlands have adopted different strategies and do not always agree with each other. Using a shared platform for water quality governance allows the Water Boards to negotiate on a shared basis, which may generate the uniformity necessary to meet the objectives of the WFD on a national scale.

This certainly does not mean that the objectives of stakeholders, employees of the Water Boards, and policy makers and the simulationists quoted above are always fully compatible. According to simulationists, a model will always be based on particular assumptions and there is no way to escape taking a particular perspective when translating the behavior of a target system into a model. An illustration of the difference between political demands and the commitments of simulationists can be found in the Harmoni-CA, which is a project funded by the EU dedicated to analyzing uncertainty in the context of the WFD. Rather than proposing one particular methodology, the Harmoni-CA project attempts to develop a variety of methods to engage uncertainty. Selecting an "adequate methodology" depends on the stage of the modeling process where uncertainty is encountered, the type, nature, and source of uncertainty, assessing the relevance of uncertainties for policy making, and available resources and level of ambition (Refsgaard et al. 2007). Thus, there appears to be room for negotiation or carefully crafting ways to do justice to the system at hand. Still, simulationists might emphasize the provisional character of simulations and models:

> "You never know what you do not know … and one might reply, that is something policy makers usually want, that you can indicate the bandwidth of the uncertainty, but the end result is based on a particular model of which you do not know what you do not know, right? So you can vary the input of the model and use that to represent the bandwidth of uncertainty, but the uncertainty in the *structure* of the model that is due to simplifications, you cannot make that visible." (Interview Simon Groot, April 29, 2009, emphasis added)

In other words, engaging uncertainty in simulation practice is not just a statistical problem (e.g. related to input values), but can also concern the very design of the model and the way in which it aims to describe its target system.

Another, less subtle, discrepancy between the priorities of stakeholders, employees of the Water Boards, and policy makers and that of simulationists revolves around scale. As Victor van den Berg explained, Water Boards do not always have the resources to deal with local issues related to water quality: such issues may require additional research, though Water Boards may not always have the resources to do so. The responsibility for allocating resources to additional research lies with *Rijkswaterstaat*, but local questions often fall outside of their area of interest, revealing a political dimension of scale:

> "[*Rijkswaterstaat*] will at times not take a very detailed look at a particular area, while the Water Board in question does not feel responsible for paying it a lot of attention. Only specific areas, the gems of the Water Board, get that level of attention, others do not." (Interview Victor van den Berg, May 19, 2009)

From a national and European perspective, it is crucial to achieve some degree of homogeneity. The WFD Explorer deals with WFD-related measures on the scale of river basins, but it is not self-explanatory that this scale does justice to the multitude of levels implicated in implementations of the WFD. For example, upstream measures can have downstream effects, which requires an overarching view. (Mostert et al. 2009, 30)

However, many measures have local effects, and information about these effects is usually only available on a local level. In addition, legal responsibilities and competencies for implementing measures may be spread across different levels of policy making, and legal requirements do not always match financial possibilities (Ibid. p. 31). The focus on river basins can also lead to the exclusion of social actors from the process of water quality governance: regional sounding boards often did not feel their ideas had an impact on the process of drafting RBMPs, which was due to the aggregation those plans inevitably introduce and a lack of formal competencies on the part of these sounding boards (Junier 2010, 43). Another cause might be the "institutional boundaries between ministries, cost, and the fear of committing to measures." (Behagel & van der Arend, forthcoming, quoted in Junier 2010, 42) Local knowledge of members of the Water Boards, stakeholders, or the general public may not always be included in RBMPs, and even if they are, it is uncertain whether their inclusion will contribute to water quality governance due to the other interests at play in the drafting of RBMPs.

What counts as working?

Although the developers focused more on enhancing the knowledge rules implemented in the calculation core of the WFD Explorer and improving the user interface, this did result in a model that proved difficult for users to work with. Towards the end of 2008, the development of the draft versions of the RBMPs needed to be complete. Reeze and Vlieger (2009) conclude that the WFD Explorer had either not been used or had been used only to a very limited extent in the process of drafting the RBMPs. It appears that the developers simply could not fulfill all of the demands of the different audiences, which had diverging expectations based on their personal expertise and role in the process of implementing the WFD. This section points to an important difference between on the one hand national-level policy makers and developers, who attempted to implement a systemic approach to water quality governance, and on the other hand users who were critical of this approach and favored more contextual methods. For the WFD Explorer to become a 'success' as a policy instrument, the Water Boards needed to accept it unanimously. Policy makers saw the WFD Explorer as a way to attain a degree of unification between the different Water Boards, while the developers attempted to develop a standardized approach to water quality governance (meeting user requirements as well as they could in the process). Although the national and systemic approach to water quality sufficed in the eyes of the developers, each Water Board had its own preferences, organizational culture, and tricks of the trade that it wanted to incorporate into the process of drafting RBMPs. For some ecologists, the top-down approach implied by the WFD Explorer was utterly unacceptable: ecology needs to start from the level of individual bodies of water, preferably even from a smaller scale. According to these ecologists, a model is simply nonsensical if it is not based on the particularities of local situations - that is, if one decides to use a model at all. In the case of the users who did want to use the WFD Explorer, it was not always clear for the developers how to meet their requirements. Some users simply wanted a repository of representations of ecosystems, measures, and the costs of measures they could experiment with, while other users wanted a model that would propose measures to them, based on the requirements of the WFD. Yet another group wanted a model that could analyze water quality-related issues in detail. What counts as 'working' here appears to consist of only partially compatible ideas among policy makers, developers, and the varying demands of users at the Water Boards, some of whom did not want to use the WFD Explorer altogether.

5.3 Thresholds of expertise

After its implementation, the WFD Explorer provoked discussions about water quality governance, which led to debates about what knowledge was still needed to properly draft RBMPs: what is a good status of an ecosystem? How can the status of ecosystems be measured and monitored? And how may the status of ecosystems be influenced by various measures? The quality of knowledge embedded in the WFD Explorer was questioned throughout the process of its development and implementation, which led to additional research into phenomena related to water quality. For example, STOWA initiated the Water Mosaic program in 2008, which is planned to continue for 10 years. In addition, various monitoring programs were set up in order to acquire more data for the purpose of validation and verification of ecological models.

Positive outcomes notwithstanding, it is not self-explanatory that technical improvements will make participatory water quality governance a reality, e.g. by updating knowledge rules, improving the design of the WFD Explorer, and making organizational changes that will create a more fertile ground for the WFD Explorer. The fact that most Water Boards expressed interest in using the WFD Explorer can be seen as proof of a demand for such an instrument. However, this demand was not shared unanimously. An important reason for Water Boards to use the WFD Explorer was that they needed to meet requirements related to the WFD. As I show in this section, expertise may pose challenges to participatory water quality governance that cannot easily be solved by new and improved designs of the WFD Explorer.

The feasibility of participation

The perceived success of the Planning Kit that was mentioned earlier created support for the WFD Explorer. As mentioned above, the use of participatory forms of modeling is not prescribed by the WFD, but rather seen as a fruitful way for 'experts' and 'non-experts' to collaborate by means of supposedly transparent instruments of governance. However, many simulationists I encountered expressed their concern about attempts to bridge gaps between different user groups, which they commonly divide into 'experts' and 'non-experts'. Attempts to enable collaborations between simulationists and their audience require "frequent and intense dialogue" and may improve "the mutual understanding of each others [sic] problems and considerations." (Icke et al. 2006, 112) Enhanced communication between modelers and water managers can be enabled by "agreement on modeling objectives in advance of applications … mutual understanding of the capabilities of model codes and the requirements of management tasks … selection of appropriate model codes … an appropriate assessment of performance to determine model credibility" (Hutchins et al. 2006, 19), although good outcomes cannot be guaranteed.

However, simulationists do not always approach the transfer of their knowledge to policy arenas as optimistically as the foregoing authors suggest. It is not uncommon for simulationists to question whether policy arenas can really do justice to the complexities and uncertainties implicated in the process of modeling ecosystems. A problem that is often mentioned is the difference between the priorities of simulationists on the one hand and stakeholders, decision makers, and policy makers on the other. This issue has already featured in the previous section: national-level policy makers saw the WFD Explorer as a powerful way to standardize water quality governance that would bring about standardization, efficiency, and political credibility. However, various users of the WFD Explorer were much more skeptical of attempts to develop such general solutions for water quality-related issues. A related issue is the way in which these different groups evaluate the outcome of models: whereas simulationists tend to interpret the output of models as a rather provisional form of knowledge, decision makers and policy makers intend on grounding their decisions on model output and demand clear-cut answers. In the following, I show that the possibility of participatory water quality governance is certainly not embraced unanimously, but still in popular demand due to a variety of benefits attributed to it.

The question-driven, research-oriented practice of modeling often seems miles apart from the focus on solutions and clear-cut answers favored by decision makers and policy makers. Many interviewees stressed a degree of incommensurability between simulation practice and the world of policy making. For example, Hans Los noticed a shift from more fundamental research to applied research during his career. According to him, it became more difficult over time to explain to policy makers that certain issues required more research. In addition, the timeframe of studies on the effects of anthropogenic influences on ecosystems has decreased to a period that typically covers the next one to four years. Los stresses that this is a timeframe connected to the rhythm of decision making and political credibility. Scientific studies usually require a longer period in order to provide more elaborate claims on patterns of events occurring in ecosystems. According to Los, the narrow timeframe that is now dominant limits the ability of simulationists to do more fundamental research into the properties of ecosystems – usually there is simply not enough time to enhance one's calculations or develop new methods. Los finds this "troubling" and laments the lack of long-term vision of policy makers who could for example initiate research programs of three to five years in order to provide a substantial analysis of an ecosystem. In an era that Los describes by referring to "strict monitoring of budgets" and the requirement for "continuous feedback", there is not a lot of understanding for exceeding the time and resources allocated to a research program: "there is usually a budget before questions are thoroughly formulated rather than the other way around … which exerts quite a bit of pressure on policy-related studies." (Interview Hans Los, May 6, 2009)

Monitoring and experimentation in addition to modeling can be a way to improve knowledge about water quality. As Luca van Duren of Deltares has stressed, simulation practice should involve an ensemble approach that consists of modeling, measuring, and experiments that together yield an understanding of ecosystems. (Interview Luca van Duren, May 18, 2009) According to van Duren, modeling, monitoring, and experimenting are all pieces of a larger puzzle. Leaning on one of these activities will inevitably introduce bias into your ideas about your subject. Sharon Tatman, Section Manager Water Quality and Ecology of the Marine and Coastal Systems Unit at Deltares, thinks that the approach to water quality modeling by policy makers tends to be misinformed, since policy makers mostly look at model output and do not have the expertise required to grasp the complexities and uncertainties concomitant with modeling ecosystems. As a result, an important part of the activities of biologists and ecologists at Deltares consists of a watchdog-like approach to policy arrangements that influence their activities. (Interview Sharon Tatman, 21 July, 2009)

Differing priorities and expectations

According to Simon Groot, there is no straightforward recipe for more reliable models. Groot describes increases in computational power as a "red thread" running through his career as a modeler, which covers decades. According to Groot, a modeler will always try to use all the computational resources available to him or her, but increases in computational power demand a critical attitude on the part of the modeler. Policy makers are inclined to see models as a way to understand and predict the behavior of various aspects of systems, including ecological phenomena:

> "Everything needs to be in there, including ecology. Of course that means that those models become more and more complex … you have to keep thinking about your model, how will you put that reality into your model? That model will always be a simplification … of reality. And in how far you can capture that in your chosen variables, that is the question, that is actually the uncertainty." (Interview Simon Groot, April 29, 2009)

Increases in computational power may enable a simulationist to make more detailed analyses, but some challenges remain the same: "we do not feel limited by computational power, but rather by a lack of knowledge. Right? So how you choose relevant variables, how you align the model with the real system, that is where the issues are." (Interview Simon Groot, April 29, 2009) Increases in computational power also need to be met by increased monitoring activities to avoid losing track of the increased detail of model predictions (see section 3.2). However, not all simulationists have the ability or the desire to use additional monitoring data. For example, Victor van den Berg's activities at the Water Board in Breda involve a balancing of monitoring and modeling on the one hand, and the resources available to do so on the other. According to van den Berg, the questions that the Water Boards need to address may require a carefully developed combination of modeling and measuring, "allowing us to measure less … I think it might be possible to measure less if you leave more to models." (Interview Victor van den Berg, May 19, 2009)

Simulationists and policy makers evaluate the output of models differently. Simulationists working with the WFD Explorer emphasize its value as a research instrument that can help to provide insights into the inner workings of ecosystems. Rather than seeing the output of the model as a solution to a particular problem, they tend to approach it as an invitation to test their own ideas, assumptions, experience, and when necessary perform additional research. It is a supplementary tool and its output can be enhanced by other, more elaborate modeling techniques:

> "We aspire to use the WFD Explorer, well, not as a means to calculate the truth … like we are asking, model, please tell us what to do! Rather, we use it to improve our insights. By modeling and combining your knowledge and by putting it into a model, you come to realizations. Why doesn't this work as I expected? And if so, what is wrong? Do I miss data or do I simply need to improve my analysis? Well, that is where [the WFD Explorer] is a valuable supplement." (Interview Victor van den Berg, May 19, 2009)

This points back to the modeling adage encountered in chapter 3: models cannot prove anything, they can merely show you the consequences of your own assumptions. This is also why van den Berg emphasizes that the inner workings of simulations and models need to be accessible: if you do not understand how simulations and models work, you should not use them to gain insights. Importantly, this also means that personal experience and knowledge are seen as crucial ingredients to using simulations and models in a responsible manner.

According to simulationists, policy makers sometimes tend to take model output too literally. As was the case with modelers working in the fields of hydraulic engineering and geotechnical engineering, simulationists studying water quality are very eager to stress the provisional, exploratory nature of their activities, and will always judge model output on the basis of experience and tentative ideas:

> "The danger with building more and more complex models is that they are seen as representative of reality, that you cannot see anymore where the uncertainty is … it helps in your analysis of the system. But policy makers will see it as a

> representation of reality, like 'the model says', then it becomes certainty" (Interview Simon Groot, April 29, 2009)

Groot argues that knowledge of ecological phenomena is "by definition" incomplete, "we do not have complete knowledge of the system, how things interact … you can do a lot of calculations based on your assumptions, which yields an answer, but you have to keep thinking about your assumptions." (Interview Simon Groot, April 29, 2009)

By acknowledging the provisional nature of knowledge created by means of simulations and models, simulationists also point to the danger that the model output may be taken literally. Alfred North Whitehead used the term 'misplaced concreteness' (Whitehead 1997) to refer to this phenomenon. According to Whitehead, people commit the fallacy of misplaced concreteness when they mistake an abstract belief, an opinion, or a general concept about the way things are, for a physical or concrete reality. When someone mistakes model output for 'reality', he or she commits the fallacy of misplaced concreteness. As indicated in chapter 2, critical studies of simulation practice often approach simulation practice in terms of mimesis and representation: simulations and models fail to do justice to the complexity of reality, and are therefore 'dangerous' or 'problematic'. As became clear in the previous section, ecological models are especially vulnerable to this critique due to the complexity of their target systems (e.g. Pilkey & Pilkey-Jarvis 2007). As I explained in preceding chapters, simulationists often do not aim to develop highly accurate representations. The question is rather how models function as means of presentation or intervention, and what motives and interests can lead social actors to confuse models with 'reality'.

Distributions of expertise

The ability of model users to critically approach model output forms a criterion by means of which simulationists differentiate between 'experts' and 'non-experts'. More generally, differences between experts and non-experts play an important role in the lack of consensus pertaining to the WFD Explorer. Sandra Junier's work on the WFD Explorer reveals that distributions of expert knowledge influenced its development and implementation. Junier claims it is unlikely the Water Boards will achieve consensus regarding the design of the WFD Explorer. According to her, this emphasizes the need for a pragmatic approach to the development of the WFD Explorer, which means that a relatively small group of developers takes care of the model's design. However, based on her observations in the field and her own professional experience, Junier also thinks that the 'richness' and 'depth' of ecological questions justify the influence of this smaller group. According to her, it is understandable to address more detailed questions related to the design of the WFD Explorer in a smaller group of 'experts', and subsequently allow a broader audience of stakeholders, employees of the Water Boards, and policy makers to use the WFD Explorer to examine ecological issues in broader, more general terms. (Interview Sandra Junier, June 4, 2009) The manual of the first version of the WFD Explorer also explicitly states that attempts to meet local particularities (e.g. by changing input values and using different calculations for particular areas) should be limited, since this would create a confusing plethora of versions of the WFD Explorer.

Junier's remarks regarding the degree of involvement of stakeholders, employees of the Water Boards, and policy makers thus echo the ideas of those more skeptical of the degree of standardization that widespread use of the WFD Explorer would imply. After all, both Junier and model skeptics argue water quality modeling is a 'complex' process due to the large amount of interdependent processes, which apparently can only be fully appreciated by those 'in the know'. The difference between Junier and model skeptics is that the latter think the complexity of ecosystems restricts the area where the WFD Explorer can be applied, whereas Junier does not rule out the possibility of successful applications of the WFD Explorer in advance. However, expertise may yield thresholds between social groups that can be difficult to bridge: during her encounters with skeptical ecologists, Junier witnessed that this skeptical group of potential users found that the WFD Explorer required their assistance in day to day use: "they think their own expertise needs to function as a filter … they rule out that policy makers can eventually use such a model themselves, while this is the goal of a number of these kinds of models." (Interview Sandra Junier, June 4, 2009). Piet van Iersel encountered similar issues:

> "It all depends on whether you are dealing with an expert or a policymaker … an expert knows very well that a model is a model and that it has its limitations. However, policy makers […] cannot understand those models, that is impossible […] yet they are confronted with the output of models. I think they are unable to say, yes, it is true what the model calculated, it is good or bad. In other words, they thus become dependent upon experts who are knowledgeable." (Interview Piet van Iersel, June 12, 2009)

Simulationists frequently refer to the importance of expertise when describing their encounters with stakeholders, decision makers, and policy makers. For example, René Boeters, a civil engineer working at the *Waterdienst* of *Rijkswaterstaat*, has participated in an international board of biologists, ecologists, and hydrologists who have written a report on the salinization of the *Volkerrak Zoommeer*, a fresh water lake in the southwest of the Netherlands. The board evaluated a number of models that were used extensively by local authorities responsible for the *Volkerrak Zoommeer*. Boeters stresses these models remained rather opaque for the people who were using them to predict future states of the lake: "it is a kind of wizardry for lay people." (Interview René Boeters, April 22, 2009) Forming the board of experts and allowing these experts to judge the issue at hand enabled a degree of trust on the part of policy makers: "They were not always happy, but they did feel more certain … this has been researched well, we will not get into trouble if we follow up on this advice." (Interview René Boeters, April 22, 2009) Although simulation practice remained in the hands of the members of the board of experts, the local authorities were convinced that this differentiation in expertise would work in their favor. Apparently, simulations and models do not only function as the means for exploration and learning, but also contribute to making things 'true' and thereby help to close a debate. Boeters' account of the use of models in the context of studying algae growth in the *Volkerrak Zoommeer* makes clear how priorities and responsibilities are structured around the use of models.

The differentiation of responsibilities and knowledge may have important repercussions. According to Leo Postma, a water quality modeling expert working at Deltares:

> "It is not only the case that those who make decisions generally do not have sufficient expert knowledge, but also that those who have expert knowledge are generally insufficiently aware of the needs of decision makers." (Interview Leo Postma, June 11, 2009)

In other words, simulationists and policy makers should attempt to bridge their activities. Simulationists need to develop a stronger sense of how their work is used by policy makers, and policy makers need to have more attention for the complexities and uncertainties related to simulation practice.

In the case of the WFD Explorer, I observed similar ways in which stakeholders, employees of the Water Boards, and policy makers were involved, but in particular ways based on their supposed ability to deal with the challenges of modeling. The activities of simulationists who made use of the WFD Explorer during the process of drafting RBMPs reveals strategies of veiling and unveiling, which enact differences between experts and non-experts. Victor van den Berg described how difficult it can be to convey knowledge to an audience of non-experts. During one particular session with stakeholders, local farmers in the southwest of the Netherlands, van den Berg experienced challenges in explaining the output of a model to his audience. Van den Berg and his colleagues had recently included climatological predictions in the model, but the audience in question pointed out how the model output did not confirm their own ideas and expectations:

> "You can never completely align [model output] with the way people experience things in practice at the moment. And that makes it difficult for the farmers to take a different perspective, so that requires a lot of explanation. But ok, we do so … and that seems to help." (Interview Victor van den Berg, May 19, 2009)

Especially the use of visual material turned out to be challenging:

> "Say you have an image based on model output, and you hand it to a policymaker or put it in a report … that makes things more difficult since you need to provide a lot of explanation in order for someone to understand it correctly." (Interview Victor van den Berg, May 19, 2009)

In practice, this means that visual material is used mainly among simulationists and only rarely in reports and sessions with stakeholders: "you can tell them something, but people see an image and it will always start to lead a life of its own." (Interview Victor van den Berg, May 19, 2009)

Jaap Kwadijk, Senior Hydrologist at Deltares, reflects on the use of the Planning Kit, and argues DSSs may give a coherent overview of an issue, but their lack of depth often makes their use somewhat superficial:

> "It is like a group of people going on a trip. We collect travel guides, sit around the table with a drink, and ask where everyone wants to go, skim through some travel guides, and then agree on the destination!" (Interview Jaap Kwadijk, June 12, 2009)

Kwadijk admits this is a bit of an exaggeration, but his scientific background and experience seep through the irony of his remarks. Policy makers working at *Rijkswaterstaat* rarely have the level of scientific knowledge of historical figures like Cornelis Lely (see section 3.1), and simulationists point out many meetings at *Rijkswaterstaat* focus on organization rather than content. The reorganization of *Rijkswaterstaat* resulted in the move of employees of the more policy-oriented *Waterdienst* to *Lelystad*, which provided ample reason for many people to prefer working at Deltares: for some, the new location of the *Waterdienst* was simply too remote, while others preferred to work in an environment that they saw as more welcoming to research. The reduction in the number of scientists at the *Waterdienst*, especially those working on the marine environment, has also made it more difficult for employees at Deltares to put research on ecosystems on the agenda. A lack of expert knowledge make lobbying for research money all the more challenging, especially if your research occasionally delivers more questions and blind spots rather than concrete answers. This is not an uncommon result of research on ecosystems, and of research more generally. (Interview Sharon Tatman, July 21, 2009) Kwadijk observes that the attempt to delegate research to other institutions and companies may have "gone too far." Model output often fulfills an important role in policy making, and it is not uncommon for policy makers to demand a certain consistency in model output and exert pressure on institutions like Deltares. Kwadijk describes how this can sometimes seem rather far-removed from earlier times when engineering and policy making seemed to be intertwined more intimately. Policy making seems to take place around seductive yet treacherous concepts like 'sustainability' and 'resilience', while engineers struggle to make these concepts tangible and applicable by doing research and developing models. (Interview Jaap Kwadijk, June 12, 2009) Working at Deltares increasingly also requires the skill to translate one's expertise to a more general audience of stakeholders, decision makers, and policy makers.

The relationship between simulationists and their audience does not just relate to distributions of (expert) knowledge, but also how different social groups involved with simulation practice characterize each other. Only a particular group is allowed to contribute to the content of the WFD Explorer, and participation involves a process of translating 'expert' knowledge to 'non-expert' audiences, which shapes the interactions of stakeholders, employees of the Water Boards, and policy makers with the WFD Explorer. Some modelers have the desire to develop tools to either educate stakeholders, employees of the Water Boards, and policy makers, while others repeatedly refer to boundaries related to priorities and experience that may preclude stakeholders, employees of the Water Boards, and policy makers from making informed decisions. Although many interviewees did not completely oppose participatory forms of modeling, they did point out complications with differing degrees of severity. 'Expertise' appears to be a notion that draws boundaries between different user groups, based on how 'experts' experience their interaction with 'non-experts': users of the WFD Explorer (and simulations and models more generally) need to have some kind of expertise in order for them to evaluate model output 'responsibly'.

Differences in priorities and expectations notwithstanding, many interviewees expressed enthusiasm about the value of participatory modeling. According to Junier, the WFD Explorer is a typical example of the kind of "tools" that are needed. Ecologists are simply not used to the level of transparency that is more common in other fields, such as flood risk management. Due to the high population density in the Netherlands, measures required to counter flood-related risks often involved issues related to spatial planning. By making the impact of those measures accessible to stakeholders, employees of the Water Boards, and policy makers by means of models, engineers have become more accustomed to using models to make expert knowledge available for a broader audience. In that sense, the implementation of the WFD is a rather new phenomenon, and perhaps something that ecologists and biologists have yet to get used to. (Interview Sandra Junier, June 4, 2009) As I show in the following section, a degree of enthusiasm is retained in the development of the new version of the WFD Explorer.

5.4 Redesigning the WFD Explorer

As described in section 5.1, the process of developing the WFD Explorer featured a sincere effort of its developers to incorporate as many user demands as possible. This caused the WFD Explorer to shift from a crude model aimed at facilitating debate to a more elaborate instrument for detailed analysis. Since the WFD Explorer was initially taken up by 'experts' working at the various Water Boards, all of whom continued to dispute the model's design and quality, it did not end up being used in the process of drafting RBMPs. Joost Icke stresses that the "real demand of the field", namely improved knowledge pertaining to water quality modeling, became apparent only in retrospect. (Interview Joost Icke, December 2, 2010) The developers were aware of the fact that models related to water quality contained many assumptions and uncertainties at the time, but thought the level of detail of the initial version of the WFD Explorer was sufficient for the use they envisaged. The disputes around the WFD Explorer formed an important incentive to change the model's design. In 2010, the development of a new version of the WFD Explorer started in order to respond to the criticism of skeptical model users described in section 5.2. An evaluation report that describes improvements to the future version of the WFD Explorer even suggests jettisoning the name of the model to avoid "historical ballast and negative associations." (Consortium KRW Verkenner 2009a, 9)

Designing the second version of the WFD Explorer

A steering group was established that consists of DG Water, STOWA, *Waterdienst*, PBL, the *Waterschapshuis*, and *Witteveen & Bos* in order to guide the development of the second version of the WFD Explorer. The latter two are involved in the steering group as representatives for the Water Boards (*Waterschapshuis*) and engineering consultancies in the Netherlands (*Witteveen & Bos*). The development is financed by DG Water, STOWA, and the *Waterdienst*, and is carried out by Deltares. A user group that consists of members of the *Waterdienst*, various Water Boards, *Rijkswaterstaat*, STOWA, *Waterschapshuis*, PBL, and Alterra was set up to make sure the demands of users are met. Many users of the WFD Explorer did not trust the output of the model due to a perceived lack of quality and transparency, and a substantial group of users was skeptical towards the WFD Explorer due to the degree of standardization concomitant with ecological modeling. In order to meet these objections to the WFD Explorer, several changes have been made to its design.

First of all, the new version of the WFD Explorer features an updated set of calculation rules, which were established after the developers organized meetings with various experts. The reception of the WFD Explorer made clear that there was insufficient knowledge about the various processes that influence water quality. As indicated above, the WFD Explorer played an important role in leveraging research and mobilizing resources for this research.

Second, the WFD Explorer will be integrated in monitoring programs, which have been set up to provide data that can be used to validate and verify model output. The WFD Explorer has been adapted in order to work with the results of the Water Mosaic program, which can help to validate and verify ecological knowledge rules. Although the WFD Explorer can be used to model a total of 750 bodies of water in the Netherlands, only 75 of those are actively measured. The WFD Explorer can also assist in finding out which bodies of water need to be measured additionally, or what number of measuring sites is representative for these bodies of water.

Third, it is now possible to import data from other models into the WFD Explorer, such as SOBEK and models developed in the NHI (*Nationaal Hydrologisch Instrumentarium*, National Hydrological Instruments) program. Especially SOBEK is used extensively for hydrodynamic aspects of water quality modeling (e.g. transport of sedimentation). This allows many Water Boards to continue working with their own modeling software and incorporate the output of those models into the new version of the WFD Explorer. A modular structure of the WFD Explorer will make it easier for users to adapt it to their own needs and incorporate model output from other software.

Fourth, the developers also attempted to improve the quality of the WFD Explorer by including insights from other WFD-related research. Knowledge rules from other WFD-related instruments (developed by Alterra and PBL, discussed in section 5.1) have been incorporated into the new version of the WFD Explorer. Additional calculation rules developed by Royal Haskoning have also been included in the new version. As a result, the WFD Explorer now features ecological calculations for all types of water, including brackish water. Thus, the level of detail has been expanded to include different types of bodies of water, and the interactions between different types of phenomena (i.e. ecology, biology, chemistry, hydrology). The overlap between the WFD Explorer and similar applications notwithstanding, the developers do not plan on a full cooperation with the parties involved.

Fifth, as a response to model skepticism and suspicious attitudes towards standardized approaches to water quality governance, ecologists and biologists are now actively involved in the redevelopment of the WFD Explorer.[60] Many users lamented the fact that a relatively small group of developers had such a large influence on the design of

[60] The method chosen is known as AGILE, a software development method that concentrates on iterative and incremental developments made by collaborating teams. This enables shorter phases in the process of developing software, and allows potential end users to voice potential concerns during software development.

the WFD Explorer. The developers of the new version of the WFD Explorer also attempt to make the WFD Explorer more transparent by allowing users to study its design in more detail. According to some users, the epistemic opacity of the first version of the WFD Explorer could be misleading: rather than becoming aware of uncertainties and assumptions, users could work with the instrument under the impression that everything functioned smoothly. In retrospect, the developers think these uncertainties could have been expressed more explicitly to the end users, which would have made their expectations more realistic (Consortium KRW Verkenner 2009a, 10). The epistemic opacity of the first version of the WFD Explorer is countered by allowing users to view decision trees underlying the design of the ecological knowledge rules. Although it cannot be assumed that this increase in the model's transparency will also yield acceptance, at least its users will now have the ability to inform themselves of the inner working of the model.

Sixth, expert users primarily develop the new version of the WFD Explorer with biologists, ecologists, and other professionals working at the various Water Boards in the Netherlands in mind. Stakeholders, employees of the Water Boards, and policy makers are explicitly not acknowledged as the model's primary users (Consortium KRW Verkenner 2009b, 7). The desire to bridge the gap between modelers and stakeholders, employees of the Water Boards, and policy makers turned out not to be very realistic (Consortium KRW Verkenner 2009a, 11). Interestingly, one document makes this observation under the rubric 'calculation time'. As I have shown above, the demands of users aspiring to a more detailed analysis were met, which led to increased calculation time and complexity of the application. Although this made it more difficult for 'non-expert' users to use the WFD Explorer, it was certainly not the only obstacle encountered, as I have shown in section 5.3.

Seventh, the developers have let go of their demand to create one single instrument. Reeze and Vlieger have stressed that the first version of the WFD Explorer fell between the demands of two user groups: whereas more analysis-oriented ecologists and biologists wanted more detail, stakeholders, employees of the Water Boards, and policy makers wanted an instrument that would be easier to use (Reeze and Vlieger 2009, 21). The authors recommend developing two versions of the WFD Explorer that should produce compatible output. Whereas adaptations of the first version of the WFD Explorer were eschewed due to the unmanageable outbreak of versions this would create, local versions are now portrayed as tailor-made solutions to very specific questions. In other words, the desire to develop a single, all-encompassing model has receded. In order to provide users at the Water Boards with the level of detail in space and time they desire, the developers decided to build two different versions of the new WFD Explorer: one primarily aimed at analysis on a local level, and one addressing questions related to water quality on a national level, which focuses on the costs of measures. The former version is more adaptable than the latter, and can easily be customized in order to meet local requirements related to implementing WFD-related measures. Since the model is now aimed at analysis rather than real-time results that are necessary during meetings, preventing long calculation times is no longer a strict requirement. This also creates an opportunity for the developers to meet the demand of many users, who wanted a more elaborate scientific instrument. The new version of the WFD Explorer will feature a larger set of measures and more detailed analyses. The emphasis is more on disclosing the latest ecological knowledge than providing solutions: "A far-reaching optimization of sets of measures however is beyond the reach of the WFD Explorer. Such optimizations continue to demand customization and extensive knowledge of the system." (Consortium KRW Verkenner 2009b, 7)

Eighth, developers attempt to compensate the lack of user friendliness of the first version of the WFD Explorer by enhanced means of communication. Wikis on ecology are expected to induce peer teaching (Consortium KRW Verkenner 2009b, 18), though ecologists were reluctant to formalize and share their knowledge during the implementation of the first version of the WFD Explorer. New technological interfaces are a potential additional improvement to the design of the WFD Explorer. A setting where one user sits behind a laptop and controls the model does not really work, Joost Icke says. According to him, novel user interfaces such as the Maptable (see section 3.3) and serious games (see section 4.2) may have promising effects. (Interview Joost Icke, December 2, 2010)

The developers still aim to create a future version of the WFD Explorer that functions as an instrument for participatory water quality governance for stakeholders, employees of the Water Boards, and policy makers. However, they also admit that this can only become a reality after the instrument has been further enhanced and accepted by the various users at the Water Boards. Rather than communication between 'experts' and 'non-experts', the new version of the WFD Explorer mainly emphasizes the need for further analysis. The increase in quality is also expected to eventually enhance the viability of the WFD Explorer as a tool for participatory water quality governance. Still, a lot of ecological knowledge is simply not available yet, which may require different versions and an extensive period of research.

Conclusion: standardization or participation?

The WFD Explorer can be interpreted as a site of contestation between the interests of different parties. As such, the WFD Explorer did not entail the emergence of a consensual understanding between these parties about how participatory water quality governance should proceed, but rather entailed an attempt to achieve stabilization of an instrument of governance. In terms of the three aspects of modeling practices that I chose as foci in the presentation of my empirical material (construction, validation, and communication, see section 1.3), the case of the WFD Explorer reveals a commitment to a particular kind of communication, namely participation. This commitment could not be met due to issues of trust and expertise that emerged during the development and implementation of the WFD Explorer, which became 'stuck' in the phase of construction and validation, so to speak.

The discussion of the history of the WFD Explorer presented three challenges its developers came to face. First of all, as shown in section 5.1, the attempts of the developers to meet the requirements of their user base created a confusing and chaotic process of implementation, in which the WFD Explorer suddenly had to function as an instrument for detailed research rather than estimation and exploration. This reveals a discrepancy between projected and actual use, which only became apparent after attempts to implement the WFD Explorer. Past experiences and projected benefits of participatory governance were the cause of optimism at the time, particularly on the part of national-level policy makers. However, commitments to participatory governance need to be assessed critically before assuming that the development of instruments of participatory governance will have a beneficial outcome. Secondly, in section 5.2 I explained how the WFD Explorer failed to gain the trust of its user base. Users dismissed the output of the WFD Explorer, lamented the lack of transparency of the model, and in some cases even opposed the activity of modeling ecological phenomena altogether. Since users had conflicting ideas concerning the role the WFD Explorer should fulfill, it became rather difficult for the developers of the WFD Explorer to meet the aforementioned objections. Thirdly, institutional and professional thresholds shape the practice of participation, as I showed in section 5.3. Differences in the agendas of various social actors as well as organizational and institutional thresholds can be rather persistent, and shape negotiations and collaboration between social actors. More generally, improvements to the WFD Explorer are largely framed as technical issues, which leaves insufficient attention to how participation takes place and who actually participates. It is not self-explanatory that social actors will approach the WFD Explorer and simulation practice more generally on equal or compatible terms. Simulationists emphasize the experimental and procedural character of the development of the WFD Explorer (e.g. in the form of the ongoing interaction between experts and non-experts described in section 5.4) and model output more generally. However, it cannot be assumed that national-level policy makers view the design and output of the WFD Explorer as procedural as well. Whether new and improved designs can provide a remedy for the foregoing difficulties remains to be seen.

The developers' response to the issues described in sections 5.1 to 5.3 shows that participatory water quality governance has changed from a guiding ideal to a possible outcome. However, a crucial motive underlying the development of the WFD Explorer was its perceived ability to act as an instrument for 'inclusive' or participatory governance, meaning it would include a multitude of knowledge and social actors. Although the WFD Explorer enables users to study the effects of different measures, its development is largely delegated to a more restricted group of 'experts'. Thus, the WFD Explorer can become an 'obligatory passage point' (Callon 1986) in water quality governance, which limits the latter's content and audience. The development of the WFD Explorer will require some uniformity, which might not accommodate the interests of all prospective users of the WFD Explorer. In addition, the viability of the WFD Explorer in the political arena depends on a degree of standardization, which does not necessarily correspond with the ideal of inclusive politics. Although standardization may imply exclusion, it is also needed in a political context, e.g. to enable policy making on a national or European level. Instruments of governance therefore imply a degree of standardization, and as a result do not correspond neatly with the variety of knowledge and social actors that are included in inclusive forms of politics.

In sum, the 'communication landscape' opened up by the WFD Explorer is not a smooth Habermasian space devoid of power in which ideas are exchanged, but fraught with dimensions of power that make it more 'rippled'.[61] It is crucial to study the effects

[61] In a Habermasian communicative space, various parties attempt to achieve consensus by means of communication that is, ultimately, without bias and interests (according to Habermas). For a Foucauldian critique of power-less communication, see Kelly 1994. See also Peter Sloterdijk's work on critical theory (e.g. Sloterdijk 1984).

and sources of these dimensions of power, since they shape what knowledge is included in instruments of governance and influence who is allowed to participate. Whether the WFD Explorer indeed furnishes inclusive forms of politics involves a tension between standardization and participation. If water quality governance leans more heavily towards standardization, it may reinforce existing hegemonic approaches to water quality and thereby exclude knowledge and social actors. The exclusion of knowledge and actors can put technological cultures at risk, since knowledge and actors that are potentially worthwhile are not included. However, if water quality governance leans more towards participation, its legitimacy in the political arena may be compromised since it cannot meet the requirements posed by policy making on a national and European level. Instruments of governance will involve a tradeoff between standardization and participation, and should therefore be studied in terms of exclusion of knowledge and/or actors to find out to what extent they put technological cultures at risk.

6. Conclusion

6.1 Case study summary

In chapter 3, I examined how technological, institutional, and socio-technical developments influenced model construction in hydraulic engineering in the Netherlands since the early 20th century. I showed how computational modeling gradually acquired the confidence of social groups involved with hydraulic engineering. Subsequently, computational modeling became the predominant modeling approach. I used Humphreys' notion of epistemic opacity (Humphreys 2009a; 2011) to analyze the impact of the changing apparatus of hydraulic engineering. Simulation practice, I argued, straddles discovery and manipulation, and may imply immersion (see section 2.3). Social actors involved with simulation practice may exhibit the ability and/or willingness to reflect on the impact of simulations and models on their understanding of the world. However, the advent of computational modeling and the subsequent growing complexity of models have made it increasingly difficult for social actors to reflect on the design of simulations and models. Still, hydraulic engineers engage models in a highly reflexive manner that I identified as the 'craft of modeling', although engineers are not exempt from immersion. The codification of knowledge (e.g. in the form of computer software), which can be seen as a form of blackboxing (see the introduction to chapter 3), enabled the dissemination of models to social actors outside of the engineering environments where models are developed. These social actors may have less ability and willingness to reflect on the design of models. Despite the critical and reflexive approach to simulation practice by hydraulic engineers, epistemic opacity and the issue of immersion are defining characteristics of simulation practice.

In chapter 4, I studied the validation of geotechnical models of dike failure mechanisms, and asked to what extent uncertainties that emerge in this process of validation are acknowledged. My analysis started from modeling practices in Deltares' geotechnical laboratory, where modeling is very much aimed at developing an elaborate understanding of dike failure mechanisms. Subsequently, I looked at data-intensive approaches that rely heavily on large quantities of data and computational power. Such approaches may yield knowledge about dike failure mechanisms that is considered to be e*pistemically robust*, even though geotechnical engineers remain critical of this promise. Additionally, data-intensive approaches may also improve reactive approaches (e.g. evacuation) to dike breaches that are *socially robust*. The increasing popularity of approaches that are socially robust is much to the dismay of engineers who advocate preventive approaches. Finally, I studied how Dutch dike safety policies are formulated around the various forms of uncertainty encountered in geotechnical engineering. Although uncertainty calls into question the effectiveness of various measures against dike vulnerabilities (research, adaptive measures, and preventive measures), I argued that a more elaborate understanding of uncertainty can be fruitful to improve the safety of flood defenses in the Netherlands. Dike safety policies should not so much aim at improving resilience (defined in the narrow sense, see section 1.2) since this could imply a 'stubbornness' that can put The Netherlands at risk. Rather, dike safety policies should be aligned with uncertainties in such a manner that they remain open to knowledge that arrives in the form of uncertainties, thereby cultivating adaptive capacity.

Finally, in chapter 5, I studied the development and reception of the WFD Explorer, which was designed as an instrument for participatory water quality governance. Its developers expected the WFD Explorer to create an 'inclusive' platform (see the introduction to chapter 5) aimed at a variety of parties (e.g. ecologists, biologists, decision makers, stakeholders, and policy makers). Developing the WFD Explorer required striking a balance between standardization and participation: whereas some degree of standardization was mandatory for the successful implementation of the WFD on a national and European scale, the WFD Explorer also needed to be adaptable to local requirements. The first version of the WFD Explorer that emerged from this process of development failed to reach its intended audience: the model did not acquire the trust of its envisioned user base, and differences in expertise precluded different stakeholders from using the WFD Explorer as a shared space for negotiations pertaining to the WFD. As a response, a second version of the WFD Explorer was developed that emphasized analysis rather than communication. Thus, tensions between standardization and participation eventually led to the exclusion of knowledge and actors from the development and use of the WFD Explorer, which as a result did not function as an inclusive space for devising policies related to water quality.

As became clear in the foregoing, 'thick descriptions' (see the conclusion of chapter 2) of simulations and models can reveal technological, institutional, and socio-political aspects of simulations practice. This was used to draw attention to three vulnerabilities related to simulation practice that may put technological cultures at risk: immersion, uncertainty, and exclusion. These vulnerabilities were further refined in the conclusions of the case studies (see table 6.1).

Case study	Hydrology and hydrodynamics (Chapter 3)	Geotechnical engineering (Chapter 4)	Ecology (Chapter 5)
Central aspect of simulation practice (see section 1.3)	Construction	Validation	Communication
Potential accident	Flooding, failure of coastal structures	Dike breach and subsequent flooding	Ecological deterioration
Vulnerability	Immersion (epistemic opacity ⇔ reflexivity)	Uncertainty (resilience ⇔ adaptive capacity)	Exclusion (standardization ⇔ participation)
Section	6.2	6.3	6.4

Table 6.1 Summary of empirical material

My case studies indicated how simulations and models are constructed to acquire an understanding of risks, how simulations and models acquire reliability according to various social groups, and how simulations and models function as instruments of governance. The case studies thereby point back to the notion of 'pragmatic constructions' that I raised in section 1.1. Simulations and models turn out to have a double meaning. Chapters 3 to 5 presented the pragmatic considerations of simulationists, and how the latter often use simulations and models in an exploratory manner. However, the case studies also indicate how simulations and models are located on a slippery slope that leads from their role as exploratory knowledge instruments to a more representative role in which they acquire iconical value and come to function as 'stand-ins' (Küppers et al. 2006, 21) for their target systems. As a result, technological cultures are rendered vulnerable.

The following discussion will show how the notions of immersion, uncertainty, and exclusion can be used in an analysis of simulation practice and its repercussions on technological cultures in terms of vulnerability. The applicability of immersion, uncertainty, and exclusion is not restricted to the individual cases from which I derived them. Immersion turned out to be a recurrent problem in all of the case studies, which showed that models increasingly travel outside of their contexts of development to other environments. The ability of simulations and models to travel outside their context of development, as well as the growing complexity of simulations and models, shape the ability and/or willingness of social actors to reflect on simulation practice. The reliability attributed to simulations and models featured prominently in chapter 4, but also came to the fore in chapters 3 and 5. The reliability of simulations and models is valued differently in different contexts: although engineers interpret models in terms of reliability rather than truth, representation becomes a more important characterization of simulations and models outside of their context of development. Although the exclusion of knowledge and actors featured primarily in chapter 5, chapters 3 and 4 also provided examples of exclusion: only particular kinds of knowledge were taken up in simulations and models aimed at a broader 'non-specialist' audience.

Since immersion, uncertainty, and exclusion can contribute to a study of vulnerability in technological cultures, constructivist studies of vulnerability and simulation practice do not lack hope in technical, scientific, and social progress per se, as various authors who accuse STS of 'cryptonormativity' claim (e.g. Radder 1998; Winner 1980; and to a lesser extent the work of Feenberg, e.g. 1991; 2003; 2010). Rather, studies of simulation practice can deploy the notions of immersion, uncertainty, and exclusion, and thereby leverage discussion about vulnerabilities.

6.2 Immersion

As I argued in greater detail above, simulations and models will always imply some degree of inscription, which makes it all too easy to critique simulations and models in terms of the violence they impose onto phenomena that are staged in simulation practice. Throughout the book, I chose not to focus exclusively on the inscriptive aspects of simulations and models, but also on the attitudes and actions of social actors involved with simulation practice. I asked whether and how social actors reflect on the design of simulations and models in chapter 3, how different social actors assess the reliability of simulations and models chapter 4, and how various social actors experienced the organization of governance around simulations and models in chapter 5.

Immersion can be addressed by asking whether epistemic opacity is a concern of social actors: the latter may be unable or unwilling to reflect on the design and impact of simulations and models. It is therefore uncertain whether actors are indeed interested in issues posed by immersion, especially given the perceived success of simulations and models in terms of predicting and explaining risks. The notion of inclusion (Bijker 1987) can be helpful in terms of addressing epistemic opacity and immersion: hydraulic engineers have a high degree of inclusion in a technological frame where simulations and models are approached reflexively and critically. However, other social actors may have a lower degree of inclusion in the technological frame of engineering, and as a result may be less equipped or willing to scrutinize the design of simulations and models and their output.

Critical attitudes of certain social actors notwithstanding, it is important to assess reflexivity in the light of simulations and models that are becoming increasingly epistemically opaque: it is becoming more and more difficult for social actors to fathom the calculations underlying a given simulation or model.[62] In this context, Grüne-Yanoff and Weirich reflect on how epistemic opacity influences simulation practice:

> "Because simulations are typically based on calculations that are intractable, the results of a simulation cannot be predicted at the time when the simulation is constructed or manipulated. This allows seeing the simulation as an unpredictable and opaque entity, with which one can interact in an experimental manner. However, the legitimacy of a computer simulation still relies on the analytic understanding of at least the underlying mathematical equations, if not the computation process itself. Thus, the experimental approach to simulations consists in a strategic move to "black-box" (Dowling 1999, 265) the known program and to interact 'experimentally' with the surface of the simulation." (Grüne-Yanoff & Weirich 2010, 26)

My discussion of simulation practice in hydrology and hydrodynamics showed that simulations and models are becoming more and more opaque to simulationists. The value of the aforementioned modeling adage 'models cannot prove anything, they can only show you the consequences of your own assumptions' bears witness to critical engagement with simulations and models. Simulationists indeed appear to 'interact experimentally' with the 'surface' of simulations and models. Immersion surfaces when simulationists or other social actors involved with simulation practice take model output for granted, and do not consider the more and less hidden designs on which the functioning of simulations and models relies.

The idea that the surface or appearance of technologies and even everyday practices harbor a more elaborate background that remains hidden from view is a recurrent topic in various philosophical studies of technology, and reveals epistemic opacity as a more general characteristic of technological practice. Heidegger distinguishes between *Vorhandenheit* (or 'presence-at-hand', Heidegger 1962, 26) and *Zuhandenheit* (or 'readiness-to-hand', Heidegger 1962, 98), and stresses that most objects are 'ready-to-

[62] Recall that Humphreys (2009a and 2011) rules out this understanding altogether. See the introduction to chapter 3.

hand' since they are taken for granted in everyday use, where they form hidden or withdrawn aspects of reality. 'Readiness-to-hand' then refers to "equipment that remains concealed from view insofar as it functions effectively." (Harman 2010, 18)[63] As Heidegger points out, we live in a state of *Geworfenheit* ('thrownness', Heidegger 1962, 174) in which our tacit everyday doings involve objects whose 'readiness-to-hand' is something we are thrown into. To illustrate his argument, Heidegger discusses a hammer: a piece of equipment used by carpenters to build houses, a process that also involves nails, planks, human users, and methods used by architects. People who inhabit a house once it is completed do not need to know anything about hammers or nitty-gritty details concerning the craft of carpentry. Even though everyday actions may be based on networks of technological objects, they need not be hamstrung by the complexities of such networks. Everyday actions may imply a degree of ignorance, which

> "allows us to take our tools for granted; we don't even notice them *as* objects, most of the time. We rely on their 'equipmental effect', forgetting that this efficacy is itself the result of a vast network of alliances, mediations, and relays." (Shaviro 2011)

Similarly, the issue of immersion in simulation practice concerns the fact that simulationists are thrown into and entangled in technological practices, and are increasingly condemned to understanding the surface of simulations and models that feature an opaque underlying design. Abandon all hope, ye who enter the domain of simulation practice? Not necessarily: in the following, I show how technological breakdown and reflexive practice can provide a counterweight to immersion.

Technological breakdown may draw attention to technologies that are normally taken for granted, since the moment of failure renders them obtrusive and reveals

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63 Heidegger's essay, *The Question Concerning Technology* (Heidegger 1977) criticizes technology more generally for reducing things to their presence-at-hand: "all objects are reduced to a single mournful feature: their superficiality in comparison with the withdrawn depth of being." (Harman 2010, 22) Modern technologies, such as hydroelectric dams, imply an instrumental orientation to the world that transforms the world into a *Bestand* ('standing reserve'). This orientation to the world that transforms it into a calculable surface that can easily be manipulated is identified as *Ge-stell* ('Enframing', Heidegger 1977, 19; Heidegger 1994, 24-45). In today's societies, things increasingly only have meaning insofar as they are incorporated into this Enframing. Although Enframing is advanced as the essence of technology, this essence "is by no means anything technological." (Heidegger 1977, 4) Rather, Enframing turns the world into a 'standing-reserve' of material and energy that can be calculated and stand at the disposal of humanity: "technology is one face of being itself: the face that is not withdrawn but tends to reveal itself in presence." (Harman 2010, 22)

previously veiled causes for failure (see for example the work of Snook discussed in section 1.2). Latour's notion of blackboxing denotes that technologies and scientific practices that start out as controversial matters of concern can end up as self-evident matters of fact that are no longer noticed – until something goes awry. For this reason, Latour suggests we should "arrive before the facts and machines are blackboxed or we follow the controversies that reopen them." (Latour 1987, 258) Similarly, rather than being preoccupied with the moment and subsequent aftermath of breakdown, researchers of vulnerability will be interested in how an individual, organization, or system is put at risk in the first place. However, the success of technologies and scientific practices may also render them invisible. The perceived success of technologies can contribute to immersion, since it is less likely that epistemically opaque technologies will be questioned if they are considered to function reliably and well. The opening of black boxes may therefore depend on technological malfunctioning or the uncovering and disentangling of technological practices by a diligent researcher. Judging from the previous remarks on blackboxing, immersion appears to be a problem that to some extent eludes studies of vulnerability in technological cultures: there is no knowing subject outside of the sphere of influence of technologies, and these technologies may not be questioned since they are considered to be functioning according to expectations.

Rather than merely focusing on technological breakdown, those interested in immersion should focus on the role of technologies in knowledge production and the various ways in which practitioners interact with these technologies.[64] For example, Baird remarks that technologies should not be analyzed instrumentally, but rather should be seen as "constitutive of scientific knowledge in a manner different from theory, and not simply 'instrumental' to theory." (2004, 1) Baird echoes Latour's concerns about blackboxing when pointing out that "[t]he materiality of instruments only surfaces in their making and breaking." (Ibid. p. 146) In this regard, "blackboxing renders the material transparent" (Ibid. p. 164), since it veils the complexities underlying technologies.[65]

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[64] Collins argues that studies of science should focus on human language communities: "it is important to remember the difference between the human and the non-human and to remember that it is only humans who interpret what the outputs of instruments mean." (Collins 2010, 146) The problem with this method is that it could render epistemically opaque technologies invisible to the concern of social scientists, since it falls outside of the interests of social actors using these technologies. I therefore propose a stronger emphasis on the tools and instruments used in technoscientific practices as a fruitful way to engage immersion.

[65] Baird advances a particular interpretation of laboratory studies, in particular the work of Latour and Woolgar (1986), which he accuses of falsely interpreting "the telos of science and technology exclusively in

Craft-like approaches to simulations and models earmark reflexive forms of technological practice in the face of epistemic opacity. Simulationists display various forms of critical engagement with simulations and models. Rather than studying model output or interacting with the surface of a given model, simulationists are often tempted to study the principles on the basis of which the model was designed. The term 'tinkering' (Knorr Cetina 1981) denotes the active engagement of scientific practitioners with their objects of study, which are usually recalcitrant and require active intervention on the part of scientists. Studies of tinkering in technological practices can also reveal how practitioners engage creatively with the technologies that are crucial to their day-to-day activities. For example, Almklov discusses how 'decontextualization', or "the creative activities that combine all kinds of information at hand in each context into local singular meanings" (2008, 876) is a crucial part of the use of standardized data sets in the context of offshore subsurface oil drilling:

> "When trying to place data in context, multiple levels of interpretation come into play. These interpretations do not simply add up the available data, but instead take part in a creative process in which data are tools. To be meaningful, such tools must be recontextualized whenever they are applied to new cases." (Ibid. p. 890)

The epistemic opacity of simulations and models may be unyielding, but there is a group of simulationists that engages in tinkering. Although, simulationists straddle discovery and manipulation, this need not necessarily lead to a pessimistic view of simulation practice, especially when reflexivity and tinkering are a prominent part of simulation practice. Critical engagement with simulations and models in the form of reflexivity and tinkering can contribute to what Coeckelbergh calls 'imaginative capacity', or "the development of moral imagination, which can help engineers to know the further consequences of their actions, to put themselves in the places of others outside their profession and to envision more action possibilities." (Coeckelbergh 2010, 177)

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literary terms." (Baird 2004, 7) Baird is certainly not the only scholar to stress the semiotic aspects of Latour's work (e.g. Amsterdamska 1993; Hagendijk 1996). The semiotic background of the work of Latour and Woolgar (and Latour's own work) notwithstanding, one could also defend the claim that laboratory studies and actor-network theory are well-equipped to analyze the materiality of technoscientific practices, and could thus lead to a fruitful re-orientation to technological objects.

The disconnection between mind and hand stressed by Turkle and Sennett (see section 2.3) need not be tantamount to immersion. Spuybroek (2011) places the work of Sennett in a broader perspective on technology, which displays

> "the belief that we can humanize machines by slowing them down, refraining from their continuous use, alternating their use with authentic home- and handcrafting, or using them on a less massive scale … the point is not to make the same machine do the same thing more slowly, at a human pace or in a friendlier way, but to make machines do things differently … We should look carefully at how human action organizes itself around machinery, how machinery organizes and even institutionalizes action, and how it slowly takes away or enables freedom." (Spuybroek 2011, 49)

Reflexivity and tinkering can only counter the effects of epistemic opacity *to an extent*, since they take place within the bounds of technological designs that are shaped by institutional and socio-political factors. In other words, there is always a degree of technoscientific ignorance within which reflexive practice takes place, which is therefore not a matter of mastering technologies. Rather, reflexivity and tinkering need to be interpreted as a form of situated making-do, and need to be studied in the way proposed by Spuybroek. Still, the perceived reliability of simulations and models can make it less likely their design and functioning will be questioned. What is more, communication and participation may be organized around simulation practice in such a way that possibilities for reflexivity and tinkering are limited.

6.3 Uncertainty

The second case studied model reliability and tensions between heuristic value of models and model 'truth'. Geotechnical models feature various uncertainties that turn out to be rather persistent. Funtowicz and Ravetz (1993) characterize present-day scientific practice as 'post-normal' due to the uncertainties it faces. Uncertainties pose tremendous challenges to risk assessments, and demand a stronger intertwining of scientific research and policy making, as well as the active extension of the peer community of scientific practices to include actors who have a stake in risk assessments produced by scientists. Funtowicz and Ravetz stress the need for a more inclusive process of co-creation of knowledge that should not be restricted to scientific communities.

Brugnach et al. (2008) elaborate on what a stronger focus on uncertainty in adaptive water management entails. Since “uncertainty cannot be understood in isolation, but only in the context of the socio–technical–environmental system in which it is identified” (Ibid.), Brugnach et al. propose a ‘relational concept of uncertainty’, which

> “involves three elements: […] an object of perception or knowledge (e.g. the socio–technical–environmental system) […] one or more knowing actors (e.g. a decision maker) for whom that knowledge is relevant; and […] different knowledge relationships that can be established among the actors and the objects of knowledge.” (Ibid.)

Brugnach et al. propose a relational framework featuring three types of ‘uncertainty knowledge relationships’. First, uncertainty may be due to the fact that the behavior of systems can only be predicted to a limited extent. Second, social actors may have incomplete knowledge of a system at a particular point in time. Third, the social actors involved may have incompatible frames of reference when speaking about the system in question. Adaptive water management should not attempt to cancel out uncertainties: “[h]andling uncertainties shifts from elimination toward exploring other options by reconsidering our relation to the water management situation and the other actors involved.” (Ibid.)

This ‘communicative’ approach still leaves three aspects of uncertainty unaddressed. A first objection is that Brugnach et al. do not make a distinction between ‘epistemic’ and ‘ontic’ uncertainties: whereas the former is a consequence of incomplete or fallible knowledge, the latter is a more fundamental claim about the unknowability of systems due to their indeterminate or variable properties. (Petersen 2012, 52) The distinction between epistemic (that can be reducible or irreducible) uncertainties and ontic (irreducible) uncertainties may change over time. Knowledge production is subject to technological, institutional, and socio-political influences, so that uncertainties that were previously deemed irremediable may turn out to be amenable to study after all. Rather than accepting a rigid bifurcation between epistemic and ontic uncertainties, or discussing whether systems are fundamentally unpredictable, social scientists should study how social actors arrive at claims pertaining to epistemic and ontic uncertainty, e.g. by looking at the dynamics between these two types of uncertainties, and the extent to which different social actors contest this demarcation.

Second, the sources of epistemic uncertainty can and should be studied in greater detail than Brugnach et al. suggest. Petersen (2012) distinguishes a number of sources of uncertainty in the case of climate modeling. Uncertainty may be traced back to conceptual and mathematical models, since the ways in which systems have been schematized and formalized may establish or enhance uncertainty. What is more, model input (e.g. data, observations) may be a source of uncertainty. Finally, the technical implementation of the model may introduce uncertainties, for example, in the form of uncertainties related to an experimental setup, or coding errors that may or may not be resolved. However, sources of uncertainty may also be less amenable to quantification, such methodological diversity in simulation practice, and value diversity between social groups involved with simulation practice.

Third, different social actors or social groups may value model output differently. Brugnach et al. identify this issue as 'ambiguity', but treat "the views that prevail as only one of the many possible ways of interpreting and solving a problem." (Brugnach et al. 2008) Ambiguity therefore requires water managers "to allow different relations to emerge" through "reflection, dialogue, and negotiation." (Ibid.) This is a rather optimistic view of governance that was criticized in chapter 5. MacKenzie's (1999) work on the 'uncertainty trough' has made clear that actors may have different interpretations of uncertainties, depending on their position relative to a particular socio-technical practice. Shackley and Wynne (1996) show how climate scientists talk about uncertainties in a way to leverage communication and cooperation between climate science and policy makers. Knowledge about the limitations of those models and the accompanying uncertainties decreases when models move from the context of development to policy arenas. The use of visualizations of model output can issues regarding uncertainty more accessible to a broader audience. However, simulationists will often refer to visual information as a way to persuade social actors outside of the technological frame of model development, and proceed visual information in a critical and reflexive fashion.

Petersen's typology of uncertainties (see table 6.2) can inform studies of the relationship between simulation practice and uncertainties. This typology encompasses both the design of simulations and models and social practices pertaining to them, and can help to identify sources of uncertainties across the board without focusing exclusively on particular aspects of simulation practice (e.g. model input, model validation, institutional and socio-political aspects of simulation practice).

Sorts of uncertainty

UNCERTAINTY MATRIX		Nature of uncertainty		Range of uncertainty (inexactness/imprecision or unreliability/inaccuracy)		Recognized ignorance	Methodological unreliability	Value diversity
Location/source of uncertainty ↓		Epistemic uncertainty	Ontic uncertainty / indeterminacy	Statistical uncertainty (range chance)	Scenario uncertainty (range of 'what-if' options)		- Theoretical basis - Empirical basis - Comparison with other simulations - Peer consensus	- General epistemic - Discipline-bound epistemic - Socio-cultural - Practical
Conceptual model								
Mathematical Model	Model structure							
	Model parameters							
Model inputs (input data, input scenarios)								
Technical model implementation (software and hardware implementation)								
Processed output data and their interpretation								

Table 6.2 Typology of uncertainty in simulation. Adapted from Petersen 2012, 51.

This broad take on uncertainty can be used to engage the various ways in which simulation practice relates to uncertainties. As became clear in chapter 4, the role of geotechnical modeling shifted from exploratory to representative. Various uncertainties played center stage in the different steps of the modeling chain I presented, and caused other uncertainties to feature less prominently. For example, although geotechnical engineers stress the uncertainties related to modeling soil morphologies, these uncertainties featured less prominently in discussions about evacuation procedures. Thus, Petersen's work can inform an inquiry into the various forms of uncertainty that accompany simulation practice, show what uncertainties are addressed at what stage in simulation practice and related practices (e.g. decision making, policy making), and what interests are involved. This is especially important when uncertainties cascade through the chain of activities that make up simulation practice, e.g. experimentation in the laboratory, the development of computer software on the basis of these experiments, and finally policy making on the basis of uses and benefits attributed to this software.[66]

My discussion of geotechnical modeling indicated that model output comes to be perceived as accurate by various social actors, the recalcitrance of the natural world notwithstanding. Similarly, the accuracy and reliability of data-intensive methods and software developed in the context of flood risk management is based on claims about a recalcitrant social world, i.e. the conduct of individuals that turned out to feature 'indeterminacy', caused by "real open-endedness in the sense that outcomes depend on how intermediate actors will behave." (Wynne 1992, 117) Epistemic and social robustness depend on the perceived tractability and predictability of natural and social phenomena.

As much as the tractability and predictability of various phenomena can be questioned, it may not be in the interest of social actors to do so. The successful deployment of quantitative methods in the natural science has spread to politics, economics, and other scientific disciplines, and has over time installed an unyielding and widespread belief in the power and authority of quantification (Porter 1995). Computer simulations have "formed true closed worlds, entirely within the machine, which could threaten to engulf or replace the larger world they initially sought to model." (Edwards 1996, 312) Edwards' metaphor of 'closed worlds' rings true when one keeps in mind the prevalent idea that uncertainty concerns a lack of knowledge that needs to be met by additional quantitative research, especially when risks are concerned (see section 1.2).

[66] Giorgi (2005) discusses cascading uncertainties in climate change prediction.

However, doing more research may not be in the interest of social actors, since it may increase awareness of previously unknown risks or risks whose importance was underestimated, which raises more issues rather than diminishing them. In addition, phenomena of which technological cultures are ignorant cannot be quantified and turned into probabilities, since they fall outside of the scope of quantitative practices in technological cultures.

Gross identifies uncertainty as "a situation in which, given current knowledge, there are multiple possible future outcomes" (Gross 2010, 3), and laments the widespread aversion to uncertainties. Rather than taking a 'wait and see' or 'wait-until-more-science-is-available' approach to uncertainties, Gross discusses the value of social experiments in the field of ecological design, where surprises are deliberately fostered and appreciated as moments where the precariousness of objectivity becomes apparent. As a result, social actors can become aware of ignorance, identified as "[k]nowledge about the limits of knowing in a certain area", which "[i]ncreases with every state of new knowledge." (Ibid. p. 68) Surprise can reveal the limits of knowledge, and thereby make social actors aware of phenomena that fall outside of existing modes of knowledge production. In this sense, acquiring new knowledge can also imply more ignorance. Social experimentation does not aim to "overcome or control unknowns but to live and blossom with them." (Ibid. p. 34)

The foregoing discussion on Petersen's typology of uncertainty and Gross' notion of social experimentation raises the question to what extent simulation practice acknowledges uncertainties, and thereby cherishes the potential of uncertainty and ignorance as a source of knowledge. Although uncertainty and ignorance can put technological cultures at risk, a failure to recognize their value as sources of knowledge can put technological cultures at risk. Still, the promise of uncertainty and ignorance to acts as sources of knowledge may be kept at bay as a tantalizing promise that turns out to be difficult to realize in practice:

> "The challenge ahead is that new knowledge creates new options without delivering secure criteria for handling them. People may welcome the unexpected (since it creates opportunities for innovation), but they also seek to control, steer, or even reverse the surprising events. Understood this way, curiosity and the fostering of surprises enter a paradoxical relationship. They need to be both

> unleashed and controlled, if not at the same time then certainly in a well-organized and reflexive fashion." (Gross 2010, 5)

In other words, uncertainty and ignorance may simply be usurped by vested interests, especially since quantitative approaches still turn more heads in policy arenas. As Gross himself admits, social experimentation needs to be supported by "tightly and carefully planned legal, financial, and organizational frameworks by decision makers and policy makers." (Gross 2010, 112) This does imply social experiments need to face vested interests.

In the following section, I will further elaborate on the limitations of the model of 'procedural technical democracies' and 'inclusive platforms' advanced by Callon et al. (see the introduction to chapter 5). Procedural technical democracies are in principle more inclusive in terms of knowledge and social actors, and can thereby act as platforms conducive to social experimentation in the manner proposed by Gross. According to Callon et al., uncertainty requires "questioning and debate, notably on the investigations to be launched. What do we know? What do we want to know? Hybrid forums help to bring some elements of an answer to these pressing questions." (Callon et al. 2009, 21) However, the use of simulations and models as technologies around which procedural technical democracies can be designed may also hinder the inclusion of a multitude of knowledge and social actors. If so, inclusive platforms that deploy simulations and models may have a diminished capacity to foster uncertainty and ignorance as worthwhile sources of knowledge.

6.4 Exclusion

Critiques of liberal representative democratic institutions argue the latter are running out of steam, in particular in terms of recognizing or responding to controversies concerning science, technology, and expertise. (Jasanoff 1990; Wynne 1996; Brown 2009; Callon et al. 2009) Such controversies call for extended public participation: "a pithy summary of this aspiration is that the technical is political, the political should be democratic, and the democratic should be participatory." (Moore 2010, 793) As became clear in chapter 5, the WFD Explorer was designed to establish such a democratic and participatory form of governance, which attempted to gain political purchase by establishing 'hybrid forums' that include a multitude of knowledge and actors. The development and implementation of the WFD Explorer were studied in order to outline underlying design values and political goals. The effect of the WFD Explorer on simulation practice and its broader institutional and socio-political aspects can avoid a celebratory account of participatory knowledge production. More generally, unconditional adoption of technologies that are supposed to enable participation could veil the exclusion of knowledge and actors. For this reason, the technologies underlying participatory governance and knowledge production should become the explicit focus of studies of participation and exclusion. What present-day studies of participatory governance and knowledge production can aid in thinking how technologies structure various practices, and thereby open up new vistas to study the exclusion of knowledge and/or actors?

Work on 'boundary objects' (Star & Griesemer 1989; Fujimura 1992) and 'trading zones' (Galison 1996 and 1997) looks at how social actors engage in practices around a particular object or technology, and can thereby aid in describing the role of simulations and models as mediators between social groups. Van Egmond and Zeiss (2010) discuss how models function as boundary objects in the context of policy making in the Netherlands. The function of models described by van Egmond and Zeiss echoes the role usually attributed to boundary objects, which "inhabit several social worlds … and satisfy the informational requirements of each of them." (Star & Griesemer 1989, 393, quoted in van Egmond & Zeiss 2010, 60) Models coordinate the actions of actors that inhabit different social worlds (e.g. engineers and policy makers), and manage tensions between these social worlds. Similarly, work on boundary objects shows how the latter are flexible, and thereby provide the means for different social worlds to interact whilst remaining dissimilar themselves. However, as van Egmond and Zeiss show, these social worlds do not remain stable, but are shaped by negotiations between scientists and policy makers and modeling practice. Models feature an important 'performative' component, since they do not merely establish negotiation spaces, but also function as coordination mechanisms and carriers of facts. (van Egmond & Zeiss 2010, 61) As a result,

> "models are active constituents of the context they are constructed for, be it the scientific world, the policy world, or another world … the notion of performativity may, thus, aid us in understanding how models … also actively change practices and social worlds." (van Egmond & Zeiss 2010, 70)

Work on so-called 'trading zones' (Galison 1996 and 1997) concerns the 'hammering out' (Galison 1996, 783) of rules of exchange between different social groups despite differences between these groups. Note that these differences are not overcome by means of some uniform translation of various interests, but rather concern partial communication. Trading zones can be identified as "locations in which communities with a deep problem of communication manage to communicate. If there is no problem of communication, there is simply 'trade', not a 'trading zone.'" (Collins et al. 2010, 8) Galison (1997) discusses how simulations act as intermediaries between different actors: they are objects that are pivotal in activities related to a number of different groups, and should not be seen as neutral instruments. Galison describes how simulation practice formed a site where differences were not so much overcome, but rather bridged in a way deemed satisfactory to all involved, e.g. by leading to practical results that were considered to be sufficient. In a similar vein, Mattila's discussion of 'interdisciplinarity in the making' (2005) approaches the construction of a model as an opportunity to search for commonalities shared by the social actors in question.

The work on boundary objects and trading zones can inform studies of how simulation practice shapes the interactions between social groups. The role of simulations and models as active mediators notwithstanding, users may still have some liberty in terms of incorporating simulations and models in their day-to-day practices. Merz (1999) describes modeling in particle physics as 'multiplex and unfolding', meaning models "serve multiple purposes not only in the sense of being applicable to a vast array of physics scenarios … but also in the sense of being directed toward different goals in the research process." (Merz 1999, 313) A given model, Merz argues, "occupies different places in a spectrum that is spanned by the different objects aspects, functions, and conceptions." (Ibid.) Both Merz and Knorr Cetina (2001) draw on the work of Rheinberger (1997), in particular his notion of 'epistemic things', which can be defined as "scientific objects of investigation that are at the center of a research process and in the process of being materially defined." (Knorr Cetina 2001, 88) Epistemic things lack completeness and "have the capacity to unfold indefinitely." (Ibid. p. 89) As Suchman argues, when this process of becoming acquires persistence and stability, this is due to "particular pragmatic arrangements … enacted within culturally and historically specific fields of persons and things." (2005, 394-5) Chapters 3 to 5 discussed the technological, institutional, and socio-political factors that led simulations and models to afford particular forms of usage whilst resisting others. All three case studies (the increasingly black boxed usage of hydrological and hydrodynamic models, the use of geotechnical models to furnish dike safety policies, and the deployment of the WFD Explorer to establish the means for policy making in a European context), the functioning and role of objects showed such 'pragmatic arrangements'.

Thus, although simulations and models may in principle be 'unfolding indefinitely', their use in practice requires 'pragmatic arrangements' that may or may not become hegemonic. Work on 'instrumentalization' (e.g. Feenberg 1999 and 2002; Feng & Feenberg 2008) studies the various ways in which technological arrangements are established. Instrumentalization theory can be described as "a critical version of constructivism that understands technology as designed to conform not just to the interests or plans of actors, but also to the cultural background of society." (Feng & Feenberg 2008, 112) Instrumentalization theory can reveal technological standards, or 'technical codes' (Ibid. p. 115), which harbor social demands that have shaped the design of technologies. According to Feng and Feenberg, it is the task of the researcher to excavate the norms that govern design: "by *questioning* technology vigorously, we can help open a space for *designing* technology differently." (Ibid. p. 117, original emphasis) Instrumentalization theory yields a critique of technology that aims for the development of inclusive and participatory forms of technological design and implementation.

Such calls for participation and inclusion point back to the model of inclusive politics developed by Callon et al. (2009), who argue scientific and technical controversies are becoming more abundant and impact more and more people at the same time. The general public supposedly does not have the expertise required for dealing with these issues, but the latter should not be dealt with exclusively by those considered to be specialists. For this reason, democratic institutions

> "must be enriched, expanded, extended, and improved so as to bring about what some would call technical democracy, or more precisely in order to make our democracies more able to absorb the debates and controversies aroused by science and technology." (Ibid. p. 9)

There are two ways to problematize this greater call for participation. First of all, according to Moore (2010, 794 ff.), the opposition between advocates of greater participation and proponents of more technocratic modes of decision making has rendered some of the discussions on expertise politically stale. Public engagement is by now more widely endorsed, as shown by the use of simulations, visualizations, and serious games by an audience of 'non-experts' that I discussed in chapters 3 to 5. As a result, "critiques of expertise have lost some of their political purchase." (Ibid. p. 795) The development of 'open' and 'transparent' technologies aimed at widespread participation can also be read as attempts to acquire political legitimacy.

Second, Collins and Evans (2002 and 2007) problematize calls for greater participation by arguing certain claims to knowledge are more valuable than others. They also argue that the uncritical acceptance of knowledge advanced by a multitude of social actors will not always benefit the process of decision making. The involvement of social actors in decision making, Collins and Evans argue, should be determined solely on the basis of epistemic considerations: some social actors do really know more than others. The work of Collins and Evans can also help to show how dissent (here seen as the desire to question technology) appears to be intertwined with questions related to expertise: it is likely that only those social actors who 'talk the talk' and 'walk the walk' (which Collins and Evans identify as 'interactional expertise' and 'contributory expertise' respectively) can indeed propose alternative designs.

Wynne (2002) argues Collins and Evans have a rather narrow interpretation of how scientific knowledge is constructed and how this in turn gives shape to 'expert knowledge'. The work of Collins and Evans suffers from "a neglect of context and a denial of the ultimate contingency of saliency and meaning." (Ibid. p. 404) By ignoring processes of knowledge production and how expert knowledge acquires its reliability and objectivity (as is an important component of laboratory studies, see section 2.3), Collins and Evans risk reinforcing an "authoritarian social idiom, in which public meanings (and identities) are not problematized but presumed and imposed." (Ibid.) Wynne accuses Collins and Evans of adhering to a 'realist discourse' in which questions related to knowledge are reduced to

> "questions of, 'is it true?', neglecting questions about the social purposes and objects of knowledge … one effect of realist discourse is to delete domains in which meanings might be seen to be in question, and this deletion is, by default or by intent, part of the tacit social negotiation of just these boundaries … Recognizing these omitted issues involves questions of how definitions of public issues are established and maintained, and thus what becomes salient and what is deleted from collective attention." (Ibid. p. 405)

By claiming that existing practices successfully define the meaning of issues and circumscribe groups of social actors equipped with the expertise to deal with these issues, Collins and Evans appear to adhere to the deficit model of expertise (see section 1.2). Such an approach refuses to ask how problems are framed and acquire meaning, and how publics are created around these problems.

It is exactly the study of issue articulation or agenda setting and the formation of publics that can lead to forms of critical engagement with participation. Rather than oscillating between technocracy and greater public participation, a stronger focus on how participation is constructed, such as instruments of governance like the WFD Explorer, can yield a more substantial view of how participation can lead to exclusion. The WFD Explorer has a mediating role since it provides its users with the means to explore possible future scenarios by making hypothetical predictions about future states of affairs, such as the expected impact of measures. Instruments of governance, such as the WFD Explorer, are not neutral since values about the form and content of participatory governance reverberate through their design and use. The mediating role of the WFD Explorer makes it crucial to study the values embedded in its design.

Concerning the mediating role of technologies, Orlikowski questions any rigid divide between social and technical elements. In her analysis of technologies aimed at workplace collaboration, she wishes to advance a “sociomaterial perspective”, which “would highlight how synthetic worlds are not neutral or determinate platforms through which distributed collaboration is facilitated or constrained, but integrally and materially part of constituting that phenomenon." (Orlikowski 2010, 136) Users of the WFD Explorer cannot be considered as free-floating and fully autonomous individuals since they are situated in a technical milieu that co-determines their actions and responses. A stronger focus on the construction and effect of this technical milieu is needed to avoid depoliticizing the exclusionary effects of instruments of governance. Various authors point out the need for an explicit focus on the technologies of governance (e.g. Barry 2001; Braun & Whatmore 2010; Whatmore & Landström 2011; Marres & Lezaun 2011). A stronger focus on technologies of participation can also deal with the epistemic opacity and perceived success of simulations and models, which establish thresholds for participation and social negotiation: users may be incapable or simply not interested in opening the black boxes they confront in simulation practice, or simulations and models may have acquired so much currency in practice that they cannot be contested easily. A more explicit focus on technologies of participation can make the issues of epistemic opacity and reliability amenable to analysis and critique.

6.5 Concluding remarks

In the foregoing, I have not presented catastrophes, disasters, or otherwise disconcerting events that expose the vulnerability of the Netherlands to water-related risks. Immersion, uncertainty, and exclusion are not straightforward incentives for immediate change. Rather, they provide an insight into how the Netherlands, seen as a technological culture that relies heavily on the use of simulations and models, aligns itself with various risks. As I argued in the introduction, studies of vulnerability are not so much preoccupied with dismal events, but aim at understanding features of technological cultures that put the latter at risk.

My analysis of simulation practice provides various ways to assess the effects of simulation practice on the Netherlands, and technological cultures that deploy simulations and models more generally. All case studies revealed tensions that cannot be canceled out easily, and therefore deserve continued scrutiny. The tension between epistemic opacity and reflexivity continues to imply immersion: although reflexivity and tinkering are indicators of critical engagement with simulations and models in practice, epistemic opacity remains a characteristic of simulation practice. Uncertainty can put technological cultures at risk as long as it is not appreciated as a potential source of knowledge. The forms of social experimentation needed to appreciate uncertainty as a source of knowledge are presently not yet established firmly in decision making about risks, which is partly due to differences between the commitments of engineers and policy makers that cannot be resolved easily. And even in those cases where inclusive platforms are designed to engage water-related risks, the standardization needed to make such platforms successful in practice may be accompanied by exclusion. I invite the reader to take up the set of vulnerabilities presented here (immersion, uncertainty, and exclusion), and use them to study the repercussions of simulation practice.

Studying the aforementioned vulnerabilities successfully will require a substantial unpacking of simulations and technologies, which includes not only their usage by various social groups, but also their design and implementation. Recent work on what can broadly be categorized as 'software studies' (e.g. Mackenzie 2006; Fuller 2008; Wardrip-Fruin 2009; Chun 2011) is an emerging area that is particularly promising in terms of understanding how software and society are interrelated. However, the broader appreciation and adoption of this approach will partly depend on the willingness of social scientists to become familiar with the principles of software development.

In order to understand the relationship between simulation practice and the vulnerability of technological cultures, simulations and models need to be analyzed as pragmatic constructions: simulations and models are developed with particular purposes in mind, and cannot function as all-encompassing representations of target systems. In this book, I have shown how the exploratory and pragmatic use of simulation practice is located on a slippery slope towards immersion in increasingly opaque technological practices, socially and epistemically robust explanations of uncertain phenomena that may stifle innovation, and forms of governance that can lead to exclusion of knowledge and/or actors. Analyses of immersion, uncertainty, and exclusion can provide a critical perspective on simulation practice. May this book thereby help to understand the relationship between simulation practice, vulnerability, and technological cultures. May it contribute to debunking the epistemic prowess commonly associated with simulation practice, thereby countering overconfidence in simulations and models. Finally, may it contribute to building a safer and more sustainable habitat in the face of the many aspects of present-day technological cultures that render the latter vulnerable.

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Appendix: interviewees

Interviewee	Affiliation	Date of the interview(s)
Beukers, D.	Deltares. Advisor soil mechanics and archivist.	May 11, 2009
Blauw, A.	Deltares and University of Amsterdam. Marine ecologist and PhD candidate.	June 2, 2009
Bles, T.	Deltares. Consultant and Risk Manager.	June 23, 2009
Boeters, R.	Rijkswaterstaat Waterdienst. Project Leader Water Quality Volkerak Zoommeer.	April 21, 2009
Bokma, J.	Deltares. Advisor soil mechanics and software developer.	May 5, 2009
Brand, P.	Deltares. Sales and Support Manager Deltares Systems.	May 27, 2009
de Boer, G.	Deltares. Senior researcher hydrology and hydrodynamics.	June 19, 2009
de Vriend, H.	Deltares. Science Director.	March 5, 2009
Delsman, J.	Deltares. Hydrologist and researcher water quality.	December 3, 2010
Desmit, X.	Deltares. Advisor and researcher marine ecology.	May 25, 2009
Douben, K.J.	Water Board *Brabantse Delta*. Senior Advisor Water Management.	May 19, 2009
Engering, F.	Deltares. Manager Deltares Software Centre.	May 12, 2009
Förster, U.	Deltares. Senior consultant dike technology.	May 27, 2009; July 15, 2010
Friocourt, Y.	Deltares. Advisor and researcher water quality.	May 25, 2009
Groot, S.	Deltares. Water quality system analyst.	April 29, 2009
Hack, R.	ITC. Associate Professor at Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente.	June 5, 2009
Hamer, F.	Deltares. Director SBW program.	March 5, 2009; July 15, 2010

Harteveld, C.	Technical University Delft, Faculty of Technology, Policy & Management; TU Delft Centre for Serious Gaming. PhD candidate.	March 24, 2009
Havers, B.	IBM. IT architect.	June 22, 2009
Heynert, K.	Deltares. Head of Hydrodynamics and Operational Systems Group.	June 10, 2009
Icke, J.	Deltares. Senior Researcher and Consultant, Department of Strategic Studies and Innovation Management.	March 27, 2009; December 2, 2010
Junier, S.	Technical University Delft. PhD candidate, department of Water Management, section Water Resources Management.	June 4, 2009
Karstens, S.	Deltares. Advisor policy analysis.	May 25, 2009
Kater, E.	Radboud University Nijmegen. Researcher Waalweelde program.	March 25, 2009
Knoeff, H.	Deltares. Advisor soil mechanics.	May 26, 2009
Koelewijn, A.	Deltares. Advisor soil mechanics.	June 18, 2009
Kwadijk, J.	Deltares. Senior Hydrologist.	June 12, 2009
Los, H.	Deltares. Ecologist and algae bloom expert.	May 6, 2009
Maccabiani, J.	Deltares. Program Manager Flood Control 2015.	March 24, 2009
Meijers, E.	Deltares. Advisor and researcher. Product owner WFD Explorer.	June 18, 2009
Melger, E.	Deltares. Product Manager.	May 26, 2009
Mens, A.	Deltares. Researcher and consultant soil mechanics.	June 23, 2009
Mens, M.	Deltares. Researcher Flood Risk Management.	June 2, 2009
Nagel, R.	IBM. Managing Consultant Technology Strategy.	June 22, 2009
Offermans, A.	ICIS (Maastricht University). PhD candidate.	June 3, 2009
Pals, N.	TNO. Senior Scientist TNO Information & Communication Technology.	July 30, 2009
Postma, L.	Deltares. Advisor and researcher water quality modeling.	June 11, 2009
Roest, M.	VORtech. Managing Director.	March 31, 2008; March 5, 2009

Santbergen, L.	Water Board *Brabantse Delta*. Senior Policy Advisor.	June 27, 2011
Schaminée, P.	Deltares. Advisor and researcher experimental research.	March 24, 2009
Schrijver, R.	Rijkswaterstaat. Program Manager SBW.	August 11, 2011
Smits, T.	Radboud University Nijmegen. Departmental Head Centre for Sustainable Management of Resources.	March 25, 2009
Stive, M.	Technical University Delft. Scientific Director Water Research Centre Delft.	December 2, 2010
Stout, J.	Deltares. Advisor and researcher hydrology and hydrodynamics.	June 19, 2009
Tatman, S.	Deltares. Section Manager Water Quality and Ecology, Marine and Coastal Systems Unit.	July 21, 2009
Tolman, M.	Deltares. Software developer.	May 6, 2009
Uittenbogaard, R.	Deltares. Advisor and researcher hydrology and hydrodynamics.	June 23, 2011
Van, M.	Deltares. Expertise Manager Dike Technology.	April 16, 2009
van 't Hof, B.	VORtech. Software developer.	July 3, 2009
van Beek, V.	Deltares. Advisor and researcher soil mechanics.	April 15, 2009; June 24 2011
van den Berg, V.	Water Board *Brabantse Delta*. Senior Policy Advisor.	May 19, 2009
van den Brink, M.	Rijksuniversiteit Groningen. Assistant Professor Spatial Planning.	March 18, 2011
van der Doef, M.	Deltares. Advisor and researcher hydrology and hydrodynamics.	June 4, 2009
van der Meij, R.	Deltares. Advisor and researcher soil mechanics.	May 18, 2009
van der Meulen, T.	*Waterloopkundig Laboratorium*. Advisor and researcher hydrology and hydrodynamics.	August 12, 2011
van der Waaij, B.	TNO. Consultant Monitoring and Control TNO Information & Communication Technology.	July 30, 2009
van Duren, L.	Deltares. Senior Researcher marine biology.	May 18, 2009
van Gent, M.	Deltares. Head Coastal Structures	June 4, 2009

	department.	
van Griensven, A.	UNESCO-IHE. Associate Professor of Hydroinformatics.	June 23, 2009
van Heeringen, K.J.	Deltares. Senior Consultant Operational Water Management group.	June 19, 2009
van Hoven, A.	Deltares. Project Leader soil mechanics.	May 4, 2009
van Iersel, P.	Water Board *Brabantse Delta*. Chemist and water quality advisor.	June 12, 2009
van Maren, B.	Deltares. Senior Researcher and Consultant sediment transport.	June 10, 2009
van Ruiten, K.	Deltares. Senior Advisor hydrology and hydrodynamics.	June 24, 2009
van Schijndel, S.	Deltares. Manager Operational Water Management group.	June 24, 2009
van Staveren, M.	Deltares. Risk Management Expert.	May 26, 2009
Verwey, A.	Deltares. Senior Specialist Modeling Systems.	May 27, 2009
Vrijling, H.	Technical University Delft. Professor in Probabilistic Design and Hydraulic Structures.	November 29, 2010

Samenvatting in het Nederlands

De geografische positie van Nederland is een bron van welvarendheid, maar ook van diverse water-gerelateerde risico's. De Nederlandse geschiedenis bevat verschillende voorbeelden van deze ambivalente relatie tussen Nederland en haar omgeving. Verschillende natuurrampen hebben Nederland door de jaren heen geteisterd, maar de Nederlanders hebben het vermogen ontwikkeld en verbeterd om het water (tot op zekere hoogte) te temmen. Het Nederlandse waternetwerk en haar diverse sluizen, gemalen, dammen en waterkeringen verkeren echter in een permanente staat van onderhoud. De gevolgen van een overstroming van Nederland en haar kwetsbare delta zullen desastreus zijn. Bovendien brengt de verandering van het klimaat nieuwe uitdagingen met zich mee, zoals de stijging van de zeespiegel en een toenemende hoeveelheid neerslag die door de rivieren zal moeten worden afgevoerd. Nederland mag dan ook met recht een kwetsbaar land worden genoemd.

In het inleidende *eerste hoofdstuk* van dit proefschrift maak ik duidelijk dat de kwetsbare positie van Nederland niet alleen te duiden is in termen van haar geografische positie. Nederland is namelijk een technologische cultuur in fundamentele zin: het reilen en zeilen van het Nederlandse waterbeheer en de civiele techniek is doordrongen van diverse technologieën, die een cruciale rol spelen in het garanderen van de veiligheid van Nederland. Met technologie wordt in dit proefschrift echter niet alleen het eerdergenoemde Nederlandse waternetwerk bedoeld, maar veeleer het gebruik van simulaties en modellen (kortweg 'simulatiemodellen'), die een cruciale rol vervullen in het benoemen, begrijpen, voorspellen en bestrijden van water-gerelateerde risico's. Er is dan ook een bepaalde mate van afhankelijkheid van simulatiemodellen. Daarnaast is het ook belangrijk het gebruik van simulatiemodellen onder de loep te nemen. Het simuleren en modelleren van risico's brengt namelijk een vertaalslag van wereld naar model met zich mee, hetgeen betekent dat simulatiemodellen blinde vlekken, aannames, simplificaties en onzekerheden kunnen bevatten. Simulatiemodellen kunnen een technologische cultuur kwetsbaar maken doordat zij risico's niet of niet afdoende weergeven.

Gegeven de afhankelijkheid van simulatiemodellen en de hierboven beschreven vertaalslag die het simuleren en modelleren van risico's met zich mee brengt, richt dit proefschrift zich op de volgende hoofdvragen: op welke wijze gebruiken technologische culturen simulatiemodellen in hun omgang met risico's, en tot op welke hoogte en hoe maken simulatiemodellen technologische culturen kwetsbaar?

Om mijn onderzoek naar de kwetsbaarheid van Nederland beter te plaatsen ten opzichte van ander wetenschappelijk onderzoek, bevat het eerste hoofdstuk een korte beschrijving van bestaande studies van risico, kwetsbaarheid en veerkracht. Risicostudies bestaan voornamelijk uit kwantitatief onderzoek naar de waarschijnlijkheid van gebeurtenissen die een bepaalde schade zullen berokkenen op mensen, organisaties en samenlevingen. Sociaalwetenschappelijke studies van dergelijke risicostudies laten zien dat kwantitatief onderzoek vaak niet toereikend is en dat 'risico' een kenmerkend fenomeen is van hedendaagse samenlevingen, die door middel van kwantitatieve risicostudies trachten risico's beheersbaar te maken. Studies naar kwetsbaarheid vertrekken vanuit een ander perspectief. Daarbij staat niet zo zeer de voorgenoemde formule 'kans op een gebeurtenis' maal 'de gevolgen van deze gebeurtenis' centraal, maar juist de oorzaken van een gebeurtenis met schadelijke gevolgen. Terwijl het ongeluk centraal staat in veel (kwantitatieve) risicostudies, richten studies naar kwetsbaarheid zich juist op de technologische, organisatorische en sociaal-politieke verhoudingen die schuil gaan achter een ongeluk, of beter gezegd, voorafgaan aan het ongeluk. Belangrijk daarbij is dat een ongeluk zich niet per se hoeft voort te doen in het geval van kwetsbare technologisch artefacten, individuen, of samenlevingen. Kwetsbaarheid betekent echter wel dat technologisch artefacten, individuen, of samenlevingen *vatbaar* zijn voor gebeurtenissen met schadelijke gevolgen. Studies naar veerkracht maken duidelijk dat het antoniem van kwetsbaarheid niet zo zeer robuustheid is, maar juist adaptieve capaciteit. Een robuust systeem kan namelijk simpelweg terugkeren naar haar kwetsbare beginstaat, terwijl een systeem dat adaptieve capaciteit heeft zich juist kan ontwikkelen en daardoor zichzelf weerbaar kan maken tegen gebeurtenissen die het systeem kunnen beschadigen.

Het eerste hoofdstuk besluit met een beschrijving van de onderzoeksmethodologie. Het empirisch materiaal is verkregen door middel van een etnografische studie, waarbij het bestuderen van praktijken en de opvattingen van verschillende sociale groepen centraal staat. Deze observaties heb ik aangevuld met interviews en analyses van documenten. Zoals eerder bleek bestudeer ik in dit proefschrift het gebruik van simulatiemodellen binnen technologische culturen en de mogelijke gevolgen daarvan in termen van kwetsbaarheid. Ik baseer mijn antwoorden op de onderzoeksvragen op een beperkt domein, namelijk het gebruik van simulatiemodellen in het Nederlandse waterbeheer en de civiele techniek. Daarmee is dit proefschrift echter geen verhandeling over waterbeheer en civiele techniek in Nederland in de strikte zin. Mijn discussie over het Nederlandse waterbeheer en de civiele techniek functioneert als *explanans* en niet als *explanandum*: het is mijn bedoeling de relatie tussen (toenemende) afhankelijkheid van simulatiemodellen enerzijds en de kwetsbaarheid van technologische culturen anderzijds in meer algemene zin te duiden. Daarbij dient de discussie over het Nederlandse waterbeheer en de civiele techniek ter illustratie.

In mijn discussie over het Nederlandse waterbeheer en de civiele techniek concentreer ik mij op verschillende activiteiten bij Deltares, een kennisinstituut voor toegepast onderzoek dat zich richt op diverse thema's op het gebied van water, ondergrond en infrastructuur. Waar nodig heb ik mijn onderzoek naar de activiteiten van Deltares aangevuld met observaties en interviews bij andere organisaties en het bezoeken van symposia en workshops. Het leeuwendeel van mijn etnografische studie vond plaats tussen maart en juli 2009, met aanvullende observaties en interviews in 2010 en 2011. Dit heeft geresulteerd in een totaal van 73 interviews met ingenieurs, ecologen, biologen, programmeurs, managers, bestuurders, beleidsmakers en onderzoekers bij kennisinstituten, waterschappen, overheidsinstanties en onderwijsinstellingen. In het proefschrift staan drie aspecten van simulatiemodellen centraal: constructie, validatie (het aantonen van overeenkomsten tussen simulatiemodellen en hun doelsystemen) en communicatie. De drie casussen in het proefschrift nemen elk voornamelijk één van deze drie aspecten voor hun rekening, hoewel enige overlap tussen de casussen onvermijdelijk is. In de casussen vermijd ik een perspectief dat uitsluitend technologische aspecten van simulatiemodellen beschrijft. Sterker nog, ik laat zien dat simulatiemodellen en hun rol in termen van kwetsbaarheid alleen kan worden bestudeerd en begrepen door zowel hun technologische als institutionele en sociaal-politieke aspecten te bestuderen.

In het *tweede hoofdstuk* neem ik bestaand wijsgerig en sociaalwetenschappelijk onderzoek naar simulatiemodellen onder de loep. Het begrip 'model' kan worden gekarakteriseerd als een abstracte of formele weergave van een object, proces of systeem, en heeft daardoor een brede betekenis die zowel wiskundige vergelijkingen als schaalmodellen van bijvoorbeeld gebouwen omvat. Het begrip 'simulatie' kan worden gedefinieerd als nabootsing or replicatie. Bovendien impliceert het begrip simulatie het nabootsen of imiteren van een dynamisch proces door middel van een ander proces. Neem bijvoorbeeld het simuleren van de effecten van getijden in een schaalmodel, of het voorspellen van het verloop van een overstroming door middel van een reeks tijdstappen in een computermodel.

Simulatiemodellen vereisen een vertaalslag van een onderzoeksobject (het 'doelsysteem') naar een model, waarmee vervolgens simulaties kunnen worden uitgevoerd. Mijn beschrijving van simulatiemodellen laat niet alleen zien hoe deze vertaalslag plaatsvindt, maar toont ook aan dat een simulatiemodel nooit overeen kan stemmen met een doelsysteem. Gegeven de aard van simulatiemodellen is dit ook niet opmerkelijk: wanneer het observeren van een doelsysteem als zodanig mogelijk is en ook afdoende is, is het niet noodzakelijk een simulatiemodel te ontwikkelen. Vaak wordt een doelsysteem sterk gesimplificeerd in een simulatiemodel. Bovendien richten veel simulatiemodellen zich op toekomstige standen van zaken of extreme gebeurtenissen die maar zelden of nooit geobserveerd (kunnen) worden in 'de werkelijkheid'. Veel studies bevestigen deze rol van simulatiemodellen en duiden simuleren en modelleren in termen van 'adequaatheid' in plaats van 'waarheid'. Toch concentreren veel kritische studies van simulatiemodellen zich op de vertaalslagen die het simuleren en modelleren van doelsystemen hoe dan ook met zich mee brengt. Simulaties zouden zelfs kunnen leiden tot 'immersie', een situatie waarin het onmogelijk is geworden de werkelijkheid los van simulatiemodellen te zien. Sterker nog, de werkelijkheid zou volgens sommigen ontoegankelijk worden voor diegenen die gebruik maken van simulatiemodellen.

Discussies over simulatiemodellen verwijzen in dit opzicht naar de notie van 'pragmatic constructions' ofwel 'pragmatische constructies' van Küppers et al. (2006, 21), aan wiens werk ik ook de titel van dit boek ontleen. Simulatiemodellen concentreren zich op doelsystemen die alleen kunnen worden begrepen door middel van een vertaalslag van 'werkelijkheid' naar simulatiemodel. Simulatiemodellen impliceren pragmatische overwegingen en ingrepen teneinde een systeem te kunnen modelleren en hebben een duidelijk geconstrueerd karakter. Toch kunnen simulatiemodellen als plaatsvervangers van hun doelsystemen optreden, bijvoorbeeld wanneer zij niet langer als pragmatische constructies worden gezien, of wanneer simulatiemodellen worden beschouwd als erudiete en betrouwbare representaties van doelsystemen. In de casussen die volgen op het tweede hoofdstuk gaat het mij niet alleen om het bestuderen van de voorgenoemde vertaalslag van doelsysteem naar simulatiemodel, maar ook om de handelingen en opvattingen van diverse sociale groepen die op verschillende manieren met simulatiemodellen werken. Zoals eerder aangegeven bevat mijn analyse van simulatiemodellen zowel hun technologische als institutionele en sociaal-politieke aspecten. Daarbij zal blijken dat simulatiemodellen lang niet altijd als pragmatische constructies functioneren.

In het *derde hoofdstuk* bestudeer ik het gebruik van simulatiemodellen in de hydrologie en hydrodynamica, waarbij onderzoek naar overstromingen en constructies nabij water centraal staat. De computersimulaties die momenteel het gebruik van simulatiemodellen in de civiele techniek domineren worden gekenmerkt door opaciteit: computersimulaties en hun onderliggende ontwerp zijn door de jaren heen steeds complexer geworden. Daardoor wordt het steeds minder waarschijnlijk dat ontwikkelaars en gebruikers van computersimulaties in staat zijn de onderliggende constructie van simulatiemodellen te begrijpen. Bovendien is het niet vanzelfsprekend dat ontwerpers en gebruikers deze onderliggende constructie willen bevatten, zeker wanneer computersimulaties naar behoren functioneren en worden gezien als betrouwbare kennisinstrumenten. Opaciteit kan daardoor leiden tot het hierboven beschreven probleem van immersie: gegeven de opaciteit van computersimulaties wordt het steeds minder waarschijnlijk dat ontwikkelaars en gebruikers van simulatiemodellen reflecteren op de invloed van simulatiemodellen, noch dat zij de wens hebben op dergelijke wijze te reflecteren op de invloed van simulatiemodellen.

Teneinde de invloed van opaciteit beter te begrijpen bestudeer ik eerst hoe de methode van constructie van simulatiemodellen in de civiele techniek sinds de vroege 20e eeuw is veranderd. Analytische methodes, elektrische modellen (die later hebben geleid tot het ontwerpen van de eerste analoge computers in Nederland) en schaalmodellen vormden een tijd lang parallelle trajecten in de hydrologie en hydrodynamica. De opkomst en dominantie van computersimulaties kan niet worden beschreven als een uitsluitend technologisch proces van toenemende efficiëntie, maar duidt juist op een amalgaam van technologische, institutionele en sociaal-politieke factoren die tezamen hebben geleid tot de huidige dominantie van computersimulaties. Deze analyse, die zich niet uitsluitend op de technologische aspecten van simulatiemodellen richt, trek ik vervolgens door in een beschrijving van tegenwoordige praktijken. Computersimulaties worden in het geval van Deltares op een 'ambachtelijke' wijze benaderd, waarbij hun uitkomsten voortdurend bloot staan aan kritiek. Bovendien proberen ingenieurs voortdurend te begrijpen op welke wijze een simulatiemodel is geconstrueerd en tot een uitkomst leidt. Hier duikt het probleem van opaciteit op. Computersimulaties worden inderdaad steeds ingewikkelder, en kunnen in de vorm van software ook nog eens gebruikers bereiken die een minder reflexieve benadering van simulatiemodellen verkiezen. Sociale groepen buiten het domein van de civiele techniek zijn daarmee vatbaar voor immersie als gevolg van opaciteit.

Immersie is dan ook een vorm van kwetsbaarheid die relevant is gegeven de opaciteit van de computersimulaties die momenteel de dominante aanpak vormen binnen de civiele techniek. Toch zijn er sociale groepen die een reflexieve manier van simuleren en modelleren verdedigen en zelfs noodzakelijk achten. De codificatie en disseminatie van simulatiemodellen in de vorm van software zijn dan ook potentieel zorgelijk, aangezien zij simulatiemodellen beschikbaar maken voor sociale groepen met een minder reflexieve benadering van simulatiemodellen. Immersie behelst daarmee een spanning tussen opaciteit en reflexiviteit die bestudeerd kan worden om de invloed van simulatiemodellen op de kwetsbaarheid van technologische culturen beter te begrijpen.

In het *vierde hoofdstuk* richt ik mij op het gebruik van simulatiemodellen in de geotechniek teneinde de processen die leiden tot dijkdoorbraken en mogelijke daaropvolgende overstromingen beter te begrijpen. Tijdens een evaluatieronde van de Nederlandse waterkeringen die plaatsvond tussen 2001 en 2006 bleek dat 24% van de Nederlandse waterkeringen niet voldeed aan de op dat moment vigerende veiligheidsvoorschriften. In het geval van nog eens 32% van de waterkeringen kon er geen oordeel worden geveld over de veiligheid van deze waterkeringen. Hoe is het nu gesteld met de veiligheid van de Nederlandse waterkeringen? Simulatiemodellen worden in dit hoofdstuk niet zo zeer benaderd als kennisinstrumenten die waarheden produceren, maar juist als bronnen van kennis die in verschillende mate relevant worden bevonden door diverse sociale groepen. Bovendien blijkt dat de geotechniek en het Nederlandse beleid omtrent de veiligheid van waterkeringen met verschillende vormen van onzekerheid te maken hebben.

In dit hoofdstuk concentreer ik mij op het faalmechanisme 'piping', een erosieproces waarbij de fundamenten van een dijk kunnen worden weggespoeld met een verzakking of doorbraak van de dijk tot gevolg. De activiteiten in het laboratorium van Deltares laten zien dat ingenieurs proberen te begrijpen hoe piping zich voltrekt. Dit gaat gepaard met een complexe keten van simulatiemodellen, van kleine experimenten op schaal tot experimenten op grote schaal. De uitkomsten van deze experimenten zijn echter onzeker door problemen met de verschillende proefopstellingen en schaaleffecten. Daardoor kan er (nog) geen eenduidige uitkomst worden gegenereerd over het exacte verloop van dijkfaalmechanismen, welke kunnen leiden tot een dijkdoorbraak en een daaropvolgende overstroming. Ondanks deze onzekerheden worden er rekenregels ontwikkeld die het faalmechanisme piping beschrijven en vervolgens hun weg vinden naar toepassingen buiten Deltares. Grote hoeveelheden rekenkracht en sensortechnieken worden toegepast voor dijkbewaking. Daarnaast ontwikkelt men verschillende toepassingen voor bestuurders en beleidsmakers, zoals websites, interactieve visualisaties en ‘serious games’. In dergelijke toepassingen staat niet zo zeer het begrip van piping centraal, maar juist het bewaken van dijken en evacuatieprocedures. Onzekerheden sijpelen ook hier door, bijvoorbeeld in de vorm van rekenregels die niet volledig zijn of de onvoorspelbaarheid van sociale actoren tijdens een evacuatie. Een bespreking van het Nederlandse beleid op gebied van de waterkeringen laat tenslotte een breed portfolio zien van opvattingen over veiligheid. Verschillende sociale groepen benadrukken het belang van onderzoek, adaptief waterbeheer (zoals evacuatie) en repressieve maatregelen (zoals het versterken van de waterkeringen). De voorgenoemde sociale groepen verschillen vaak sterk van mening. De verschillende belangen die op de achtergrond van geotechnisch onderzoek spelen impliceren een veelheid van uitkomsten van discussies over de veiligheid van waterkeringen. Het scala aan mogelijke maatregelen vormt echter wel de achtergrond waartegen geotechnisch onderzoek naar faalmechanismen en de waardering van dit onderzoek plaatsvinden. Het produceren van kennis over faalmechanismen zoals piping is dan ook niet alleen onderworpen aan wetenschappelijke ideeën aangaande relevante kennis, maar ook aan sociaal-politieke noties van relevantie.

In het hoofdstuk wordt duidelijk dat de verschillende benaderingen van dijkfaalmechanismen diverse vormen van onzekerheid produceren. Hoewel deze onzekerheden kwetsbaarheid met zich mee brengen, kan een meer gedegen studie van deze onzekerheden ten gunste komen van de veiligheid van de Nederlandse waterkeringen. Dit betekent echter wel dat onzekerheid moet worden gezien als een bron van mogelijke kennis en juist niet alleen moet worden weggewuifd als een zogenaamd gebrek aan kennis of een abject bijproduct van (onder andere) wetenschappelijk onderzoek. Onzekerheid impliceert dan ook een spanning tussen veerkracht (hier gedefinieerd in de meer enge zin als robuustheid) en adaptieve capaciteit. Alleen technologische culturen die adaptieve capaciteit nastreven kunnen volledig recht doen aan de mogelijk waardevolle aspecten van onzekerheid.

In het *vijfde hoofdstuk* richt ik mij op de ecologie en de studie van waterkwaliteit, waarbij de kwetsbaarheid van ecologische systemen centraal staat. Ik bestudeer de ontwikkeling van de zogenaamde KRW Verkenner, een model ontwikkeld ter ondersteuning van de implementatie van de KRW (Kader Richtlijn Water) – een Europese wetgeving op het gebied van waterkwaliteit. De KRW Verkenner is ontwikkeld als een beleidsinstrument dat een veelheid van kennis en sociale groepen moest kunnen omvatten en bedienen. Uiteindelijk is de KRW Verkenner echter niet geaccepteerd als volwaardig en toepasbaar kennisinstrument door de beoogde gebruikersgroep.

De ontwikkeling van de KRW Verkenner laat zien dat de ontwikkelaars aanvankelijk een grote groep gebruikers betrokken bij de ontwikkeling van het instrument. Na verloop van tijd werd de KRW Verkenner onhandelbaar volgens sommige beoogde gebruikers, die het instrument uiteindelijk ook niet vertrouwden. Het was voor hen onmogelijk om onzekerheden in modeluitkomsten te bestuderen. Voorts bleek dat veel beoogde eindgebruikers sterke twijfels hadden aangaande de waterkwaliteit te modelleren. Simulatiemodellen werden door deze groep gebruikers onvoldoende in staat geacht om recht te doen aan de complexiteit van ecosystemen. Meer algemeen blijken verschillen tussen sociale groepen in termen van expertise lastig te vermijden. Verschillen tussen ontwikkelaars, gebruikers van simulatiemodellen en beleidsmakers duiden op sterk divergerende en onoverbrugbare prioriteiten en belangen. Bovendien vereist het succesvol ontwikkelen en gebruiken van de KRW Verkenner in het kader van nationale en Europese beleidsvorming een bepaalde mate van standaardisatie, hetgeen betekent dat de participatie die beoogt werd niet alle beschikbare vormen van kennis en soorten gebruikers kan omvatten. De ontwikkeling van een nieuwe versie van de KRW Verkenner is meer gericht op wetenschappelijke analyse dan op participatie.

De geschiedenis en ontwikkeling van de KRW Verkenner laat zien dat het gebruik van simulatiemodellen in beleidsvorming standaardisatie impliceert. Dit betekent dat er mitsen en maren gepaard gaan met de overtuiging dat participatie een veelheid aan kennis en sociale groepen omvat. De toepassingen van simulatiemodellen als beleidsinstrumenten toont dan ook aan dat uitsluiting een mogelijke bron van kwetsbaarheid is. Immers, kennis en sociale groepen die mogelijk waardevolle perspectieven op beleidskwesties aanleveren worden niet per definitie opgenomen in beleidsvormingsprocessen. Uitsluiting betekent dan ook een spanning tussen standaardisatie (benodigd voor het succesvol ontwikkelen van beleidsinstrumenten en beleidsvorming op nationaal en Europees niveau) en participatie (vereist in termen van politieke legitimiteit en het betrekken van sociale groepen).

Het concluderende *zesde hoofdstuk* gaat dieper in op immersie, onzekerheid en uitsluiting. Immersie is een vorm van kwetsbaarheid die niet uit te bannen is. Daarmee bekritiseer ik suggesties van sociaalwetenschappelijke onderzoekers om terug te keren naar een klassiek-ambachtelijke manier van omgang met technologie. Elke praktijk waarin technologie een belangrijke rol speelt impliceert opaciteit. Het is niet mogelijk deze opaciteit geheel op te heffen. Sterker nog, enige opaciteit is noodzakelijk om technologisch-gemedieerde praktijken goed te laten functioneren. Het is belangrijk om de waarde van reflexiviteit te benadrukken als vorm van kritische omgang met technologieën die gekenmerkt worden door opaciteit. Onzekerheid is een vorm van kwetsbaarheid die aan diepte kan winnen door een gedegen studie van haar verschillende hoedanigheden en de mate waarin verschillende sociale groepen onzekerheid waarderen als mogelijke bron van kennis. Een dergelijke analyse kan helpen adaptieve capaciteit te ontwikkelen en daarmee technologische culturen weerbaar maken tegen risico's. Uitsluiting is een vorm van kwetsbaarheid die aandacht verdient gegeven de huidige populariteit van participatie en nieuwe technologieën (zoals 'serious games') in beleidsprocessen. Daarbij is het belangrijk nauwlettend te bestuderen op welke wijze participatie tot stand komt, en welke waarden op het gebied van beleidsvorming een weerslag hebben in de kennisinstrumenten die worden ontwikkeld om participatie mogelijk te maken. Een studie van de totstandkoming van beleidsinstrumenten kan laten zien hoe zij uitsluiting kunnen impliceren, en kan daarmee de mate waarin bestaande hegemonieën in stand worden gehouden door deze beleidsinstrumenten benoemen.

De casussen in mijn proefschrift laten zien hoe simulatiemodellen worden geconstrueerd om risico's te begrijpen, voorspellen, en bestrijden, hoe simulatiemodellen in verband staan met noties van relevantie en betrouwbaarheid, en tenslotte hoe simulatiemodellen worden toegepast als beleidsinstrumenten en daarmee vorm geven aan communicatie en participatie. Als zodanig verwijzen deze toepassingen terug naar de notie van pragmatische constructies die ik eerder beschreef. Simulatiemodellen hebben een dubbele betekenis. Simulatiemodellen hebben vaak een verkennend karakter en worden dikwijls op reflexieve wijze gehanteerd. Daarnaast bevinden simulatiemodellen zich op een hellend vlak waarop hun verkennende karakter plaatsmaakt voor een meer representatieve rol als betrouwbare en erudiete weergaves van hun doelsystemen. Simulatiemodellen kunnen op dat moment plaatsvervangend werken ten aanzien van hun doelsystemen, met kwetsbaarheid in de vorm van immersie, onzekerheid en uitsluiting tot gevolg. Met dit proefschrift beoog ik bij te dragen aan een gedegen kritisch perspectief op simulatiemodellen. De noties van immersie, onzekerheid en uitsluiting zoals ik die in dit proefschrift heb ontwikkeld kunnen naar mijn idee bijdragen aan een beter begrip van de relatie tussen simulatiemodellen en de kwetsbaarheid van technologische culturen.

Curriculum Vitae Matthijs Kouw

Matthijs Kouw (Amstelveen, the Netherlands, 1979) commenced his studies in Philosophy in 1999 at the University of Amsterdam, where he majored in Philosophy of Science and did additional courses at the Media Studies department. In addition, he spent two years in Berlin as part of the Erasmus exchange program, where he also wrote his MA thesis on the concept of technology in the work of Simondon, Deleuze, and Latour. After obtaining his MA in Philosophy in 2005, Matthijs went on to study Science and Technology Studies at the University of Amsterdam. He did research for his MSc thesis on RFID (Radio Frequency Identification) and data visualization at the Virtual Knowledge Studio in Amsterdam in 2006, which had at that time just started officially. When he obtained his MSc in Science and Technology Studies (cum laude) in 2006, he quickly decided he wanted to return to academia. Matthijs started working as a PhD candidate at Maastricht University in January 2008, which culminated in the book you are currently reading. During his studies and before embarking on the PhD journey, Matthijs worked in software development. Matthijs lives in Utrecht with Lonneke and their two cats, and enjoys listening to and composing experimental electronic music, as well as baking and cooking. A more detailed resume and a list of publications can be found on Matthijs' website: http://www.matthijskouw.nl