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Finding Vulnerabilities to High Water Levels and Their Drivers in an Interconnected River Delta Under Climate Change

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ABSTRACT

Climate change poses great risks to flood safety in river deltas. However, the exact development of climate change and the effect on flood levels is deeply uncertain. In this paper we show the spatial extent and the contribution of various uncertainties (i.e. sea level rise, changing discharges and lake set-up) on system deficiencies in an interconnected river delta. System deficiencies are defined as unaccepted high-water levels. We do this by application of scenario discovery combined with a delta scale one-dimensional hydrodynamic model. Comparison of water levels with surrounding embankment heights show the spatial distribution of system deficiencies, which strongly differ across different river branches and largely depend on local river geometry. Scenario discovery furthermore provides insights in the spatial distribution of which boundary conditions drive the found deficiencies.

KEYWORDS: Scenario Discovery; Deep Uncertainty; Climate Change; River Delta; Interconnectivity

1 INTRODUCTION

There is consensus in scientific literature that climate change will increase the risk of flooding all around the world (te Linde et al., 2010; Haasnoot and Middelkoop, 2012). Flooding is mentioned to be the most devastating natural disaster for human societies. In the case of river deltas, the flood risk is shown to originate from both sea level rise, as well as increased river discharges due to climate change (Ericson et al., 2006; Klijn et al., 2015).

As deltas are often densely populated, reducing flood risk is of utmost importance. However, to reduce the flood risk, it requires thorough insight in the precise kind and extent of future problems (Klijn et al., 2015). In the light of climate change, this precision is rather difficult to achieve, as future developments of the worldwide climate are deeply uncertain (Lempert et al, 2006). Deep uncertainty is characterized by Lempert et al. (2006) as the conditions where the analysist cannot agree upon the probability distributions to represent uncertainty about key parameters in the models.

To incorporate such future uncertainty in policymaking, policymakers must get insights in the impact of the uncertainty on relevant policy domains. One of the possible methods to quantify the effect of deep uncertainty is through scenario discovery (Bryant and Lempert, 2010). Scenario discovery facilitates understanding the impact of future uncertainty by concisely summarizing a wide range of future states of the world in a way that helps decision makers more clearly understand the strengths and weaknesses of candidate strategies. Another approach when confronted by deep uncertainty, is to consider a large variety of scenarios, without assigning probabilities to them (Kwakkel et al., 2010). In such case one deviates from the possibilistic approach to a possibilistic approach. This possibilistic approach proves to counter one of the main limitations of the regular scenario approach, where scenario development processes tend to overlook discontinuities and surprising developments (Postma and Liebl, 2005; Kwakkel and Cunningham, 2016). For example, extreme conditions at the border of a considered domain not necessarily describe all extreme conditions inside the river delta.

The possibilistic approach is especially beneficial in complex interconnected river systems, where the interaction between confluencing and bifurcating rivers and canals may enhance or reduce effects of boundary conditions (Welsch et al., under review). As studies regarding climate change in river deltas often only focus on either a single changing boundary (e.g. sea level rise) or on a part of the delta in isolation, the impact of discontinuities and combined effects might quickly be overlooked in a traditional scenario approach.

In this paper we make a first attempt to understand the impact of future developments affecting flood risk in an interconnected river delta. For this, we apply the scenario discovery methodology to determine which scenarios provide future vulnerabilities within the Dutch river delta. We define these future vulnerabilities as ‘system deficiencies’: scenarios in which the river system does not meet the desired criteria. We seek the answer to the following questions: (1) at which locations within the Dutch river delta are system deficiencies occurring due to uncertain future changes in hydrodynamics? and (2) which changing boundary conditions have most effect on the occurrence of these deficiencies?

1.1 Study area

In this study we focus on the rivers in the Dutch River Delta. This delta consists of the rivers Rhine and Meuse, Lake IJssel and a multitude of canals. The Rhine is the largest river and enters the Netherlands at Lobith, after which it bifurcates into the Waal and Pannerdensch Kanaal. The latter bifurcates again into the Nederrijn and the IJssel. The Waal and Nederrijn (which downstream becomes the Lek) both discharge in the North Sea. The IJssel culminates in Lake IJssel.

The river Waal receives the largest amount of discharge, roughly 2/3 of what is entering the Netherlands. The Nederrijn and IJssel split the remaining discharge in 2/3 and 1/3 respectively. This discharge distribution is set by law, as the flood safety standards are based on this distribution.

As flood protection measure, the Waal is confined at both sides by high dikes. The same holds for the IJssel, as almost the whole length of the river is embanked. Along the Nederrijn the embankments are mostly solely on the southern side, as the north side of the river is confined by higher terrain. The Lek is embanked on both sides again.

The Meuse enters the Netherlands at Borgharen. Shortly after entering the Netherlands, it splits into a free-flowing section and a shipping canal. Further downstream, both confluence again, after which the river enters the impounded section. In its final stretches, it becomes free flowing.

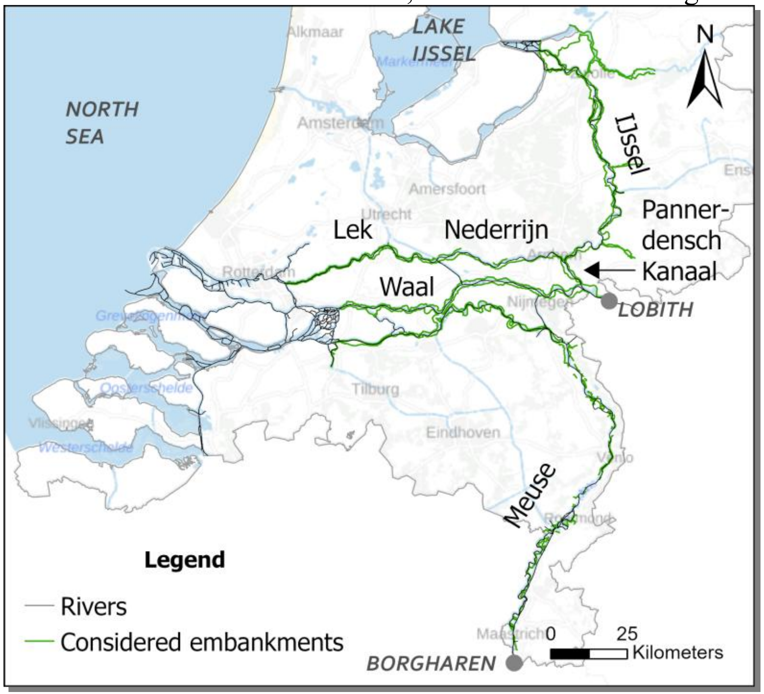

Figure 1. Rivers in the Dutch river delta and the embankments surrounding them.

2 METHOD

In line with the scenario discovery approach, first a large set of possible future scenarios is generated. Second, the scenarios are converted to water levels in the Dutch river delta using a 1D hydrodynamic model. Third, using the hydrodynamic conditions, the scenarios are filtered based on the occurrences of system deficiencies. Fourth, on the subset of scenarios where deficiencies occur, we apply a statistical data mining algorithm to find boundary conditions which produce clusters of scenarios leading to system deficiencies.

2.1 Scenarios

To draft a range of future conditions, we define a multitude of future scenarios. One scenario is defined by a unique combination of conditions at the four considered boundaries of our study area. E.g. a discharge for the Rhine and the Meuse, a given sea level and a storm surge set-up on Lake IJssel.

The scenarios are generated by sampling 2048 scenarios using a Sobol sampling scheme, assuming a uniform distribution for each sampled parameter. This uniform distribution is chosen, based on the comparisons and suggestions by Reis and Shortridge (2020) who assessed the impact of distribution choice for climate change under deep uncertainty. Since we adopted a possibilistic approach, all boundary conditions are assumed to vary independently from each other. An overview of boundary conditions is shown in Table 1.

The upstream river discharge boundary conditions are specified through two separate discharge hydrographs at the upstream model boundaries. These hydrographs are based on the Dutch standard discharge waves for the Rhine and Meuse (Hegnauer et al., 2023) (Figure 2a). We uniformly varied the peak discharge between the T100 and T10.000 return period for each river, where we accounted for the 95% uncertainty interval. The standard discharge hydrograph is scaled for each scenario based on the sampled peak discharge. For the Rhine this yields a discharge range of 11.167 m^3/s – 16.961 m^3/s and for the Meuse 2.430 – 5.120 m^3/s. We did not consider any cross-correlation between both river discharges when setting up scenarios. Additionally, on both the Rhine and Meuse, lateral inflows are neglected in this study since it is uncertain how they relate to the major rivers' discharges.

The downstream sea level is defined by an M2 water level tide, with a period of 12.25 hours and an amplitude of 100 cm, representative for the tidal amplitude at the river mouth. Since the three sea boundaries are in proximity to each other, we did not account for phase difference between the boundaries. To represent sea level rise, we superimpose the water level time series with a constant value. We thus consider climate change to only affect the base level (i.e. time-averaged water level). Changes in tidal periods and amplitudes are excluded. The range of sea level rise considered in this study is 0 – 5 m to capture future developments. A sea level increase of 5.15m is simultaneously the current T10.000 storm surge level at the river mouth.

The downstream boundary condition at Lake IJssel is defined as a stage-discharge relation (Figure 2b) where the stages are increased with a set-up based on the scenario. In case of prolonged periods of rain and/or strong winds, the water level in Lake IJssel rises at the mouth of the Ijssel. Additionally, the lake level might be increased in the future. This inclination in water level is represented in the scenarios by addition of a set-up on the stage-discharge relation. The set-up considered in this research is 0 – 2 m.

2.2 Hydrodynamic modelling

To translate the scenarios to water levels, we use a 1D hydrodynamic model, as developed by Welsch et al. (in press). To model the complete discharge hydrograph, we modelled 15 days before and after the peak discharge. To limit numerical effects, we included a spin-up period of 10 days, where the discharge is constant, equal to the discharge of the first day. We continued the simulation for ten days after the final step in the hydrograph (keeping the last river discharge constant), to let the complete discharge wave pass. In total this thus yielded a simulation time of 50 days.

Table 1. Overview of bounds used to uniformly sample boundary conditions.

	Unit	Lower bound	Upper bound
Rhine discharge	*m³/s*	11.167	16.961
Meuse discharge	*m³/s*	2.430	5.120
Sea level (rise)	*m*	0	5
Set-up Lake IJssel	*m*	0	2

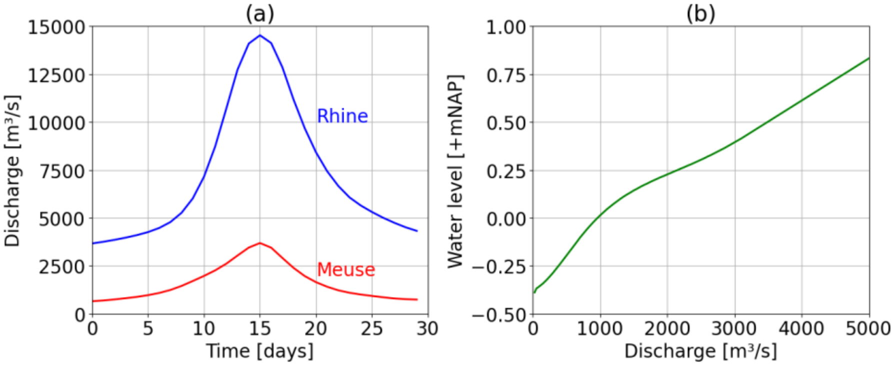

Figure 2. The reference boundary conditions in the model. (a) discharge hydrograph of the Rhine (blue) and the Meuse (red) and (b) the stage-discharge relation of the IJssel (river mouth).

2.3 System deficiencies

When defining our system deficiencies, we must determine in which cases the river system exceeds acceptable limits. As the focus of this study is on river flood modelling, we take the flood risk as indicator. Although flood risk assessment in the Netherlands is a complex method based on statistics, return periods and failure rates (Jongejan and Maaskant, 2015), we adopt a simpler approach as the scope of this research is to demonstrate application of scenario discovery in flood risk management. In this research, we consider the flood risk unacceptable in case the water level exceeds a certain threshold. This level is based on the minimum levee height along the river minus a safety margin. This safety margin consists of (a) a possible water level error due to modelling uncertainties (30 cm), and (b) a margin for wave run-up (20 cm). In summary, a system deficiency occurs if the water level along the river axis +50 cm exceeds the minimum crest height of the levee-transects in 500 m in up- and downstream direction.

2.4 Analysis

To find the combinations of boundary conditions which produce the most system deficiencies we apply the Patient Rule Induced Method (PRIM), first introduced by Friedman and Fisher (1999). The algorithm identifies subspaces (i.e. clusters) in the hyperspace spanned by the considered variables, which in this study are the boundary conditions. The subspaces are determined by hyperrectangular cubes with an upper- and lower bound for each variable which contributes to the bottlenecks. The PRIM algorithm uses a patient hill climbing optimization algorithm. In this study, we made use of the Exploratory Modelling Workbench (Kwakkel, 2017) to carry out the PRIM analysis.

In the analysis we first filtered the scenarios where deficiencies occur, as only these scenarios are of interest to us (see for example Figure 3a-b). Then, we let the PRIM algorithm find a box based on its internal optimization procedures by evaluating the peeling trajectory (e.g. Figure 3c). A balance must be found between the density (how many points within the box are of interest) and the coverage (how many of the total cases of interest are within the box) of the resulting box. This trade-off is characterized by a pareto-front: if one of them increases, the other one must decrease. For this analysis, the choice is made to select the box with the highest density, with the constraint that the marginal increase in density should be greater than the decrease in coverage (red circle in Figure 3c) along this peeling trajectory.

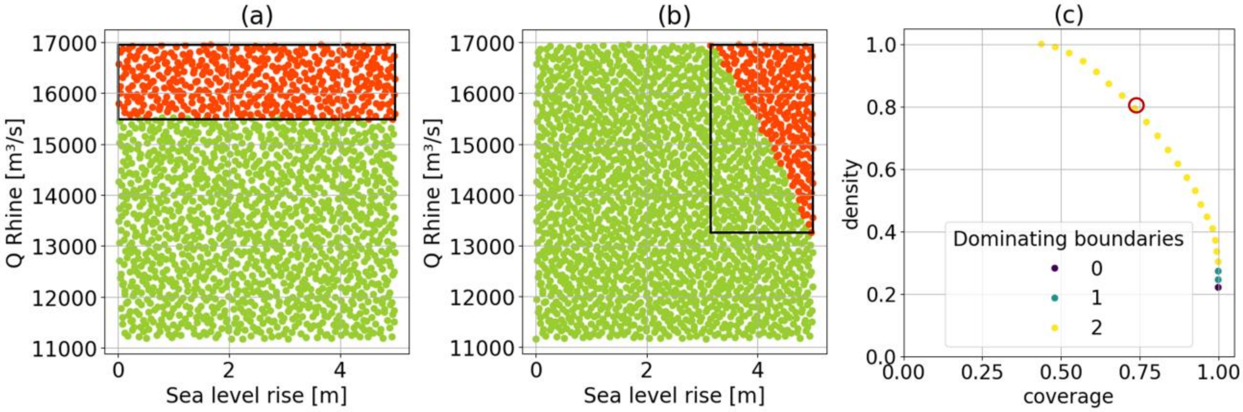

Figure 3. (a-b) Examples of scatter plots of Rhine discharge and sea level rise for two locations. The red dots represent a system deficiency. The boxes are drawn for a coverage of 1 (all deficiencies within the box). (a) shows a clear influence of only the Rhine discharge, while (b) shows dependence of both the Rhine discharge and the sea level. (c) An example peeling trajectory which displays the trade-off between coverage and density. The red circle shows the selected iteration based on the criteria in this study.

3 RESULTS

3.1 Spatial occurrence of system deficiencies

From the analysis (Figure 4) it becomes clear that system deficiencies occur along all rivers for the analysed scenarios. For each of the four major rivers, the spatial pattern differs. Most strikingly is the Meuse, where system deficiencies occur along the complete river stretch. The relative number of scenarios leading to deficiencies on this river is also very high, with the intensity centred in the northern part of the Meuse section. Partly, this might be an artefact of our analysis. This part of the Meuse naturally contains relatively few embankments as the river is constrained by higher grounds. However, at some places minor embankments are present to protect local areas (within the floodplains). As we do not consider natural elevation to be able to lead to deficiencies, only the local embankments are considered. Besides artefacts, the striking results can be explained by the design characteristics of the embankments. The embankments are designed based amongst others on a certain design discharge, based on a set return period. In this study, we vary the Meuse discharge between return periods of 100-10.000 years, while the current design discharge on the Meuse is in the lower regions of this range. It is thus to be expected that deficiencies occur for discharges which exceed the current design standard. Along the river Waal, system deficiencies also occur throughout the complete river stretch. Compared to the Meuse, the relative number of system deficiencies is much lower, but nevertheless still around 20-40%.

The patterns along the Nederrijn/Lek and IJssel differ in the sense that deficiencies occur locally. On the Nederrijn/Lek, the deficiencies mainly occur downstream. On the Nederrijn/Lek, the low percentage of scenarios leading to deficiencies is partly explained by the fact that this river stretch is only embanked at the south side of the river. In the north, the river is contained by natural higher grounds, which are not considered in this study. Thus, only a limited length of embankments is considered in this region of the analysis. On the IJssel, three very distinct clusters arise. Closer analysis shows that the deficiencies at these locations occur due to water level increase due to the local geometry of the river. The embankments do not show sudden descrease in height at these locations. At the first location, shortly after the bifurcation, the river has series of sharp bends, leading to water level set-up. At the middle and northernmost location, the water level set-up is due to a local narrowing of the river. The found deficiencies along the IJssel are thus not due to local decrease of levee heights.

The overall outcomes show that the scenario discovery approach provides insights in the spatial distributions of system deficiencies occurring on a large delta scale.

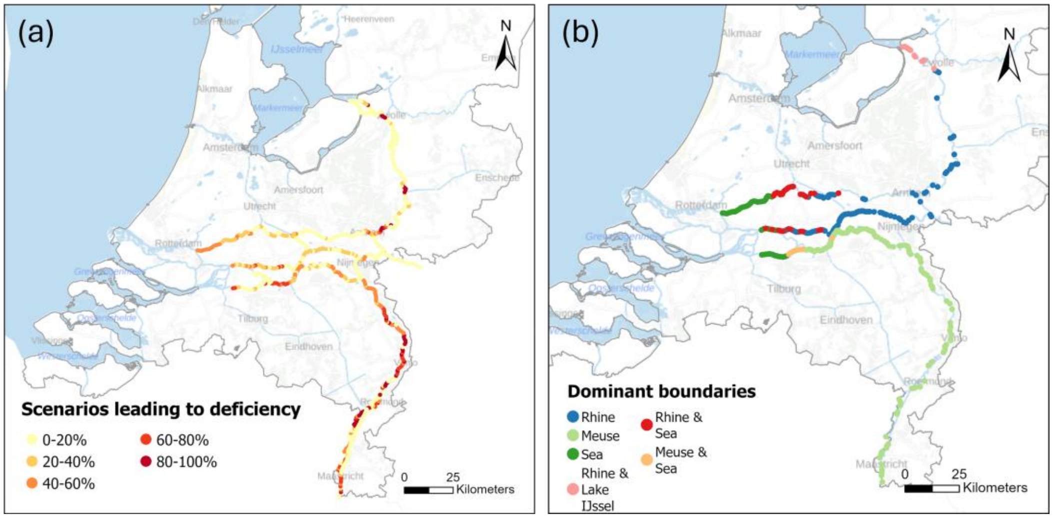

Figure 4. Outcomes of the scenario discovery: (a) fraction of scenarios leading to a system deficiency, (b) main contributors to the system deficiencies based on the PRIM algorithm.

3.2 Contributors to the system deficiencies

Application of the PRIM algorithm provides insight in the boundary conditions which contribute to the system deficiencies. Parameters which can be restricted to describe a cluster of system deficiencies in the overall outcome hyperspace are of importance. We apply this algorithm spatially as we carry out the analysis for each river kilometre independently of the others.

Outcomes show the spatial extent of the influence of boundary conditions on the occurrence of system deficiencies. In general, the arising pattern is in line with common expectations based on open channel hydraulics. In the upstream sections of the rivers, the deficiencies are determined by the upstream river discharge. At the downstream end, the occurrence of deficiencies is driven by the downstream sea level. In between both regions, there is a stretch where the deficiencies are driven both by the upstream as well as the downstream conditions. PRIM allows to spatially map out these different regions, showing explicitly where the upstream dominated zone ends and the downstream boundaries also determine the occurrence of deficiencies. However, there seems no mutual effect of both the Rhine and Meuse discharge in the downstream stretches of the Waal and Meuse. Possibly, the timing of both discharge wave is of importance here as well, which is not varied in the current study.

Another interesting observation is the difference in length of river stretch which is impacted by the sea when comparing the Nederrijn/Lek and Waal. In the flood scenarios considered, the deficiencies along the Waal are almost everywhere driven by, at least, the upstream discharge. Simultaneously, in the Nederrijn/Lek, a considerable stretch of river is mainly driven by the downstream sea level. For a physical explanation of this difference, open channel hydraulics again can provide answers. Due to the upstream bifurcations, the discharge on the Waal is trice the discharge of the Nederrijn/Lek (2/3 and 2/9 of the discharge at Lobith respectively. This larger discharge makes that the effect of the downstream boundary decreases. The PRIM analysis shows the spatial impact of this physical knowledge.

On all rivers, some isolated cases can be found as well. On the Waal for example, there are some locations where the sea level does seem to contribute to system deficiencies, while up- and downstream the deficiencies are mainly determined by the upstream Rhine discharge. Closer inspection shows the occurrence of these locations are of physical origin, due to the local geometry of the river.

One of the requirements for successful application of PRIM is that the hyperspace contains sufficient scenarios of interest. Along the rivers where only a small percentage of scenarios lead to system deficiencies, carrying out the analysis is thus not possible. Therefore, not for all considered locations outcomes are shown in Figure 4b. The locations along the river where no results are presented, contain too little number of scenarios of interest. This is in line with the lowest class shown in Figure 4a.

The opposite is also the case: the PRIM analysis shows the main drivers of the system deficiencies. As the algorithm is based on high-dimensional bump hunting, there must be made a trade-off between the coverage and density. Since we base this trade-off to favour a point somewhere along this trade-off, rather than always choosing a coverage of 1; scenarios leading to system deficiencies are excluded from the final boxes contained by the restricting boundary conditions. In other words, the presented outcomes in Figure 4b do not imply that the shown boundary conditions are the only drivers for system deficiencies at that specific location, but only the dominant drivers are shown.

4 DISCUSSION

Model wise, some remarks can be made to the presented works. As stated in the methods sections, lateral flows into the river systems are omitted. During peak flow situations, the impact of the additional discharges adds to the water levels, depending on the timing and the amount. Currently, little is known about the future developments of these lateral flows in relation to the discharge in the main river, making it difficult to assess the impact of omitting the laterals in this study. Based on analysis of a recent flood in the Meuse, the effect of the regional water system can be large. However, this was the case in an area with large gradients in elevation, which is not the case in most parts in the considered river delta.

As elucidated in section 1.1, the Dutch river delta is a complex network which can be operated to some extent through a collection of water management constructions. The hydrodynamic model operates these constructions based on the default operational rules. However, in the Netherlands, during impending floods, crisis teams at different levels of government assemble to act based on flood risks and (short-term) forecasts. Decisions taken by these crisis teams might deviate from default operations and are thus not incorporated in the presented results.

As stated in section 2.2, an oversimplification of the flood risk approach in the Netherlands has been made to illustrate the application of scenario discovery in an interconnected river delta case. In practice, flood risk design is a complex approach based on probabilities and assessment of different failure modes. The presented outcomes are thus also to be seen in that light: the presented system deficiencies do not represent dike overtopping locations or possible dike failures under future conditions. It does show the locations where the flood standards do not meet the requirements set in this study and shows its ability to relate these deficiencies to boundary conditions. For real-world applications, this definition of system deficiencies is advised to specify to better reflect design standards.

A general downside of the PRIM algorithm is that it uses a ‘patient’ hill climbing optimization procedure. Therefore, PRIM might only find a local optimum, while this is not the global optimum. To overcome this, different additional analysis techniques have been proposed (e.g. quasi p-values (Bryant and Lempert, 2010) or introducing machine learning (Kwakkel and Cunningham, 2016). Although we agree with this limitation in PRIM, we do not expect it to have major influence on the outcomes, as we do not expect multiple isolated local clusters in the outcomes. In general, increasing the considered boundary conditions leads to increased water levels. It is not expected that a further increase lowers the water levels again. Thus, this limitation is less of a concern in the presented outcomes.

The PRIM approach does add some room for interpretation for the researcher: as it is up to the user of the methodology to make the trade-off between coverage and density. In this research, a balance was strived for. However, for specific cases, the analyst, or the policy maker, might be interested in another balance: e.g. a coverage of 1 could be desired if no system deficiencies are allowed.

5 CONCLUSION

We assessed the occurrence of system deficiencies within an interconnected river delta by combining scenario discovery with a one-dimensional hydrodynamic model. We showed that on some rivers the deficiencies occur along the complete river stretch, while on other rivers the deficiencies occur only locally (driven by the river’s geometry). The most deficiencies occur along the complete Meuse. On the IJssel, the deficiencies occur in clusters, due to local river geometry. On the Waal and Lek, the deficiencies also occur along the whole river.

Additionally, the presented methodology shows the spatial influence of the uncertain boundary conditions. Overall, most part of the considered river delta is mainly driven by the upstream river's discharge. Downstream it is an interplay between the discharge and the sea level rise. Surprisingly, the interaction between the Rhine and Meuse is not dominant in system deficiency occurrence.

The overall outcomes of this study show that the methodology has the potential of providing the basis for a structural stress testing procedure to prepare future deltas for the vulnerabilities against the effects of climate change.

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