Incorporating river bed level variability into flood risk assessment: framework and application in the Netherlands

by

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Summary

The current flood risk assessment framework in the Netherlands aims at ensuring a nation-wide protection level with a long-term vision. It assumes that future river bed level changes will not pose negative effects on flood safety and it adopts a fixed-bed assumption. However, the river bed level shows a strong spatial and temporal variability and bed aggradation trends could lead to higher water levels in the future. Recent measurements in the Dutch Rhine have shown both bed degradation and aggradation in different river sections along the lower river domain. This raises questions to what implications does future river bed level changes have on flood safety in the Netherlands and whether the current fixed-bed assumption has adverse connotations to it.

The objective of this MSc thesis is to study the impact of river bed level changes on flood safety in the Netherlands. To achieve this, a framework for incorporating large-scale bed level changes into flood risk assessments is developed and applied under the current Dutch context. The implications on the long-term and short-term flood safety are analyzed separately, as fundamentally different approaches exist for the flood safety standards derivation and for the periodic safety assessment in the Netherlands. The proposed frameworks are applied to the Waal River in the Netherlands and compared against the fixed-bed assumption in the current flood safety framework.

The current flood safety standards in the Netherlands were implemented in 2017 based on a long-term flood risk assessment at the national scale. This assessment is characterized by long-term uncertainties, within a period of 50 to 100 years, which are evaluated via scenarios given their complexity. I propose to incorporate morphodynamic modelling scenarios into this long-term flood risk assessment to account for future bed level changes and their uncertainty. Modelling scenarios should include future river discharge, sea level rise, river maintenance and the evolution of river bifurcations, as they represent main drivers in the long-term river bed response in the Netherlands.

The proposed long-term framework is applied to the Waal, based on an existing long-term morphodynamic modelling study of the Rhine River. This study investigated the large-scale bed level response of the Rhine under different future climate scenarios in 2050 and 2100 considering that river dredging is not maintained after 2025. Based on these modelling results, the Waal shows bed incision over its upper river section (in the order of 1.5 m in 2100) and bed sedimentation over its lower river section (in the order of 1 m in 2100). These bed level projections yield an increment of the water levels in the lower Waal up to 0.15 m in 2050 and 0.30 m in 2100, compared to the water levels obtained under the fixed-bed assumption. Consequently, the failure probability at the dike section level, considering piping and macro instability, is estimated to be increased by up to 40% in 2050 and 90% in 2100 relative to a failure probability in the order of 10^{-2} calculated under the fixed-bed assumption. It is recommended to expand this long-term analysis with morphodynamic models that include future river dredging and future river interventions within the national planning policy in the Netherlands.

Along with the current safety standards implementation, safety assessment instruments have been developed in the Netherlands in order to assess all flood defences in a regular and uniform basis. This assessment is characterized by short-term uncertainties within 15-year periods, which are assessed via probabilistic methods to compute the failure probability of a flood defence and evaluate it against the safety standards. I propose to incorporate the analysis of the recent river bed level behaviour into the safety assessment process to account for its uncertainty in the near future. Based on yearly bed level measurements in the Waal from 2005 to 2020, general degradation and aggradation trends have been observed in the upper and lower Waal, respectively; however, bed level changes are highly variable at local spatial scales. Overall, the average bed level has been estimated to vary within a + / - 0.20 m range during the analyzed period.

The bed level variability observed between 2005 and 2020 was translated into a variability in the water levels and failure probabilities to estimate the impacts on flood safety. The bed level variability within this period leads to an increasing trend in the water levels along the lower Waal in the order of 0.05

m compared to the fixed-bed assumption. This translates into an increase of up to 10% of the failure probability at the dike section level considering piping and macro instability. The calculated increments over the lower Waal due to bed level changes are small in absolute terms; however, they are significant compared to the accuracy level of the hydraulic loads used in the safety assessment process, specified with a centimeter-accuracy, and can have important economical implications on dike reinforcement programs. It is recommended to include the water level variability from the recent past into the safety assessment model uncertainty to account for the bed level variability. To accomplish this, it is recommended to perform an analysis with more frequent bed level measurements in order to better identify the variability around the bed level trends.

In summary, this thesis provides a framework incorporating large-scale river bed level changes into the current flood risk assessment framework in the Netherlands. Furthermore, it quantifies the impacts of bed level variability on the hydraulic loads and failure probabilities in the Waal River. In general, the fixed-bed assumption in the current flood safety framework is a conservative, or safe, assumption for the hydraulic loads´ calculation in the upper Waal. However, it may underestimate the future hydraulic loads in the lower Waal and impose adverse conditions on flood safety. It is recommended to investigate the impacts of large-scale bed level changes on the Meuse River and on the other Rhine branches in the Netherlands. Finally, it is recommended to investigate other morphological processes that can impact flood risk in the Netherlands, such as bedform evolution during extreme conditions, foundation weakening due to scour, and river bifurcation instability, and complement their effects to the large-scale bed level changes investigated in this thesis.

Contents

1

Introduction

1.1. Context

The Netherlands is a low-lying country surrounded by water with a long history on flood protection. Its national flood safety approach is envisioned within the Delta Programme, whose goal is to maintain the Netherlands a safe and livable delta (Delta Programme, 2023). To achieve this by 2050, the flood defences are undergoing reinforcement as part of the Flood Protection Programme. Not only are reinforcements being carried out, but also the safety approach is undergoing research to ensure the protection level with a long-term vision.

Since 2017, new safety standards have been formulated for the primary flood defences in the Netherlands. The previous standards were defined as exceedance probabilities of the design water levels (Kok et al., 2017), whereas the new standards are defined as the allowable failure probability of a dike trajectory. The current safety standards follow a risk-based approach and consider potential flooding damages and acceptable risk thresholds. This probabilistic approach enables the treatment of a larger number of uncertainties related to flood safety. For example, the natural variability of storm surges, river discharges and the uncertainty in the strength of the flood defences to multiple failure mechanisms are accounted for, while the previous approach only focused on the design water levels.

Rivers are constantly changing their morphology as a response to natural variability and human interventions. Consequently, river morphological changes have a direct influence on all river functions, including flood safety. The morphological response of rivers is studied in the river morphodynamic field, whose interrelation with flood safety has increasingly been investigated (Vázquez-Tarrío et al., 2024). It has been found that river morphodynamics is responsible for significant uncertainties in flood risk assessment, both over the short- and long-terms. For instance, river bedform evolution during extreme events may induce a temporary higher resistance to flow and result in higher water levels (Mosselman, 2012). Long term river bed changes can result in aggradation of the main channel, leading to an increment of the water levels (Hiemstra et al., 2022; Pender et al., 2016). Furthermore, river morphology can have an impact on the strength of flood defences; for example, due to scour around their foundation, which reduces the stability of the structure (Ylla Arbós et al., 2021).

The current flood safety approach in the Netherlands assumes a fixed river bed geometry (Van Velzen, 2011; De Waal et al., 2014); nonetheless, future morphological changes can have negative impacts on flood safety. Several uncertainty sources in river morphodynamics raise challenges on predicting future river bed level changes. Besides the uncertainty in the physical morphodynamic processes themselves, uncertainty in the river controls due to climate change will play a role in the long-term. Moreover, future river management practices will also have an impact on river morphology, which further increases its uncertainty. This raises questions to what implications does future river bed level variability have on flood safety in the Netherlands and whether the current fixed-bed assumption has adverse implications to it.

1.2. Objective and research questions

The objective of this MSc thesis is to study the impact of river bed level changes on flood safety in the Netherlands.

The scope of this study is limited to lowland river-dominated systems, without significant influence from tidal processes. A case study is carried out in the Waal River, a highly monitored and investigated river in the Netherlands, and the methodology is applicable to other river-dominated systems.

To achieve the objective, the following research questions are addressed:

- How has the river bed changed over the last decades in the Dutch part of the Rhine?
- How can river bed level variability be incorporated into the current flood safety framework in the Netherlands?
- How are the hydraulic loads affected by river bed level variability compared to the current fixed-bed assumption?
- How is the failure probability of a flood defence affected by river bed level variability compared to the current fixed-bed assumption?

1.3. Research methodology

The research method is composed of three main components, as schematized in Figure 1.1. First, the theoretical background on flood safety and river morphodynamics under the Dutch context is reviewed in Chapter 2. This chapter describes the fundamental concepts within the current flood safety approach and its main assessment instruments. The river morphological dynamics in the Netherlands and their uncertainty for future predictions are further analyzed with a focus on flood safety.

Chapter 3 aims at studying different methodologies incorporating bed level changes that are best suited to the flood safety approach in the Netherlands. Both morphodynamic modelling based and measurement based methodologies are explored for predicting future morphological changes. A final approach is proposed based on the current flood safety framework and on the morphodynamic uncertainty sources under the Dutch context.

Chapter 4 and Chapter 5 present an application of the proposed approach to the Waal River in the Netherlands for the long-term and short-term flood safety, respectively. Different configurations of the river bed geometry are defined based on the proposed approach in Chapter 3. The impacts of this bed level variability on the hydraulic loads and on the failure probability are quantified. The findings are compared against the fixed river bed assumption in the current flood safety framework.

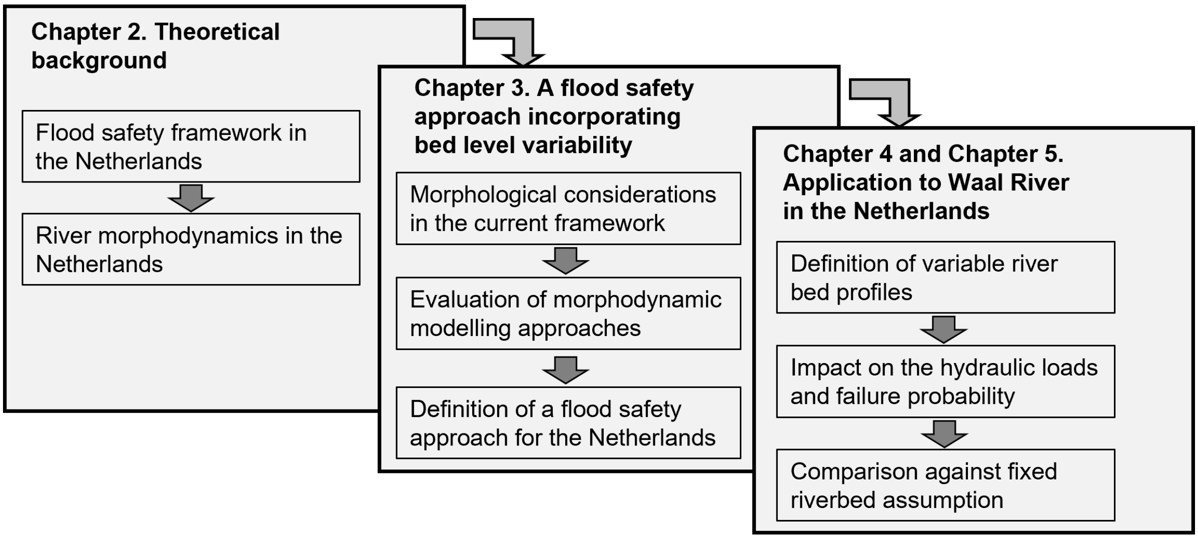

Figure 1.1: Research methodology

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Theoretical background on the flood safety framework and river morphodynamics in the Netherlands

2.1. Current flood safety framework in the Netherlands

2.1.1. Fundamental aspects of the flood safety framework in the Netherlands

Flood safety in the Netherlands is particular for its technical methodologies and management practices. On the one hand, new technical insights on the probabilistic safety assessment of flood defences have been investigated and implemented in legislation since 2017 (Jonkman et al., 2018). The analysis of multiple failure mechanisms of a flood defence, its failure probability and its risk assessment are central technical components of the flood safety framework in the Netherlands. On the other hand, new legal instruments have been developed to manage the assessment, design and reinforcement of flood defences under the new legislation (Kok et al., 2017). In this section, these main aspects of the current framework in the Netherlands are further described.

Dynamic nature

The flood safety framework in the Netherlands has continuously been influenced by the occurrence of major flooding events and the available technical methods (Slomp et al., 2022). Consequently, its basis has a dynamic nature, as new scientific research is constantly being developed and major flooding events worldwide provide new insights. However, frameworks need to be fixed in order to be applied and regulated in practice. A new framework is only translated into a new legislation once enough evidence has been found to provide a better way of assessing flood safety, even though the flood safety state of knowledge will continue to develop in a dynamic manner.

The current flood safety framework was conceived in 1956 (Slomp, 2016), implemented in 2017 and projected on ensuring a minimum protection level in 2050. This shows that the time span from conception to projection of the current framework is in the order of 50 to 100 years. It is reasonable to state that the flood safety framework will change in the future, accounting for upcoming challenges and adopting new technical findings. For example, further research on future climate models, time dependent failure mechanisms and time dependent hydraulic loads has been recommended in order to improve the current probabilistic assessment in the Netherlands (Slomp, 2022).

Besides new developments within the flood safety domain, other river functions such as navigation, freshwater supply and ecology impose changing conditions on the river system. The integrated analysis of these functions is investigated within the Integrated River Management Programme (IRM) in the Netherlands. Its objective is to identify river interventions between now and 2050 needed for these river functions, among others (Delta Programme, 2023). Therefore, river functions other than flood safety will influence the conditions under which a flood risk assessment is carried out. This dynamic behaviour shows the relevance of probabilistic approaches in order to better quantify flood safety.

Probabilistic approach

Flood safety faces intrinsic challenges due to uncertainty in flooding events. Natural variability of storm surges and river discharges, and uncertainty in flood defences reliability require the use of probabilistic approaches to quantify flood safety. Along with scientific developments, this inherent uncertainty leads to the adoption of probabilistic-based methodologies in flood safety. The advantage of a fully probabilistic approach is the added transparency to the assessment process (Slomp, 2016). The current state of knowledge, or limited knowledge, of these uncertainties can be better expressed and assessed in probabilistic terms.

The current flood safety framework in the Netherlands is characterized for its probabilistic foundation. The previous safety standards, before 2017, incorporated probabilistic approaches for the calculation of exceedance of design water levels (Kok et al., 2017). However, they were focused only on the hydraulic loads as a representation of flood safety. Since 2017, the current safety standards extend the probabilistic approach by considering both the uncertainties in the hydraulic loads as well as the uncertainties in the flood defences strength. The following sections describe in further detail how probabilistic methods are applied in the current framework.

Main components: safety standards and safety assessment

The current flood safety framework in the Netherlands can be represented by two main components: a) the safety standards and b) the safety assessment instruments. The former sets the national standards for flood safety in terms of maximum allowable failure probabilities of a flood defence, whereas the latter sets the assessment tools that are legally required to be used by water authorities (Kok et al., 2017). Both components have fundamentally different objectives and characteristics and together allow for the national flood safety assessment.

The safety standards were derived based on a long-term nation-wide flood risk assessment in the Netherlands (Vergouwe, 2016). Their purpose is to ensure a minimum level of safety along all flood defences in the Netherlands based on acceptable risk levels for the year 2050. The minimum level of safety was defined by the government considering a maximum loss of life probability due to flooding as well as an economical optimization for the reinforcement of flood defences (Van Velzen, 2011). Further details on the safety standards are described in Section 2.1.2.

The safety assessment instruments provide the technical methods to assess the flood defences in a regular basis every 12 years. They are conformed by analytical tools, software and guidelines to compute the failure probability of a flood defence based on the loads applied to it, its strength and the uncertainties involved in these elements (Slomp, 2016). The purpose of the safety assessment instruments is to provide a standardized and cost-effective process for periodic assessment of all flood defences in the Netherlands. Further details on the safety assessment instruments are described in Section 2.1.3.

2.1.2. Safety standards

Flood safety standards for all primary flood defences were set in legislation in 1996 in the Flood Defence Act (Slomp, 2016). They were updated in 2017, following a risk-based framework in response to increasing uncertainty in economic growth of cities and the development of new probabilistic methods to account for uncertainty. This section describes the main characteristics of the flood safety standards.

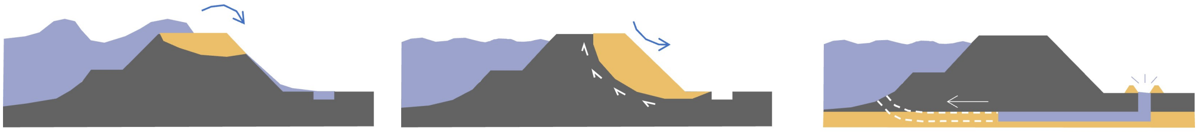
Long-term uncertainty

The derivation of the safety standards comprised a time period of 50 to 100 years from conception to projection. This long-term projection entails great uncertainty, which was taken into account in the flood risk assessment for the safety standards derivation. For example, climate change, economic growth and demographic growth were important features during this flood risk assessment (Slootjes et al., 2016). More specific sources of uncertainty such as sea level rise, river discharge and land subsidence were assessed under different climate scenarios (Van Velzen, 2011).

Probabilistic approaches have been used to quantify the uncertainty in the current safety standards. For instance, probabilistic distributions functions for the evacuation fraction, mortality rate and costs of raising dikes, among others random variables, were estimated and numerically propagated via a Monte Carlo analysis to assess the uncertainty in the flood risk assessment (Gauderis et al., 2011). Given the complexity of some long-term uncertainty sources, they can often not be represented in probabilistic terms, but rather via scenarios. In the current safety standards derivation, uncertain variables such as the future climate, sea level rise and upstream river flooding in Germany were individually varied via scenarios to assess the impact on the flood risk assessment in the Netherlands (Kind, 2011). The main objective of the scenario analysis was to screen the uncertain variables that have the highest impact on the risk assessment.

Risk-based analysis

Another main characteristic of the current flood safety standards is that they are based on risk metrics, which are defined as a function of the probability of flooding and of the consequences of flooding. The probability of flooding depends on the hydraulic loads, the strength of the flood defences, their likelihood of occurrence and their interrelation via failure mechanisms (Kok et al., 2017). Some failure mechanisms relevant in river flood defences are shown in Figure 2.1. For example, extreme water levels, the dike configuration and its material properties determine the failure probability due to macro-instability and piping (Jonkman et al., 2016). The extreme water levels are estimated via statistical extrapolation due to limited observations, whereas the material properties are expressed as random variables due to inherent soil variability.



Wave overtopping

Macro-instability landside slope

Piping

Figure 2.1: Schematic overview of main failure mechanisms in river flood defences (Kok et al., 2017)

The consequences of flooding are the second component in a flood risk assessment. In the current flood safety standards, the consequences were quantified in terms of the probability of loss of life due to flooding and in terms of economical optimal flooding probabilities (Slootjes, 2016). The loss of life depends on the flooding characteristics (water depth, water velocity, water level rising rate), the mortality rate given these flooding characteristics, and the evacuation rate. The long-term uncertainty in these variables was represented by scenarios and evaluated via sensitivity analysis. The economical optimal flooding probability was based on a societal cost-benefit analysis, comparing the costs and benefits of reinforcement against flooding (Van Velzen, 2011). This analysis depends on the economic value of the protected land, the effective damage in infrastructure given the flooding characteristics, and the costs of reinforcing flood defences. These variables where analyzed via scenarios to account for their long-term uncertainty.

Based on the flooding probabilities and consequences, three main risk criteria are defined for the current flood safety standards derivation: individual risk, societal risk and economic risk (Van Velzen, 2011). The first two of them are dependent on the loss of life probability of an individual or group of individuals, whereas the last one is based on an economical optimal flooding probability. These flooding risks are evaluated against acceptable risk levels defined by the government. The dominant, or most stringent, of these risk criteria determines the safety standards for every flood defence in the Netherlands.

Decision-making component

Decision-making plays an important role in different components of the current safety standards derivation process. For example, a projection for the climate scenario had to be chosen for the flood risk assessment in 2050 (Kind, 2011). In this regard, a warming trend scenario in the future climate was considered to calculate sea level rise in 2050, which was in agreement with the national planning policy in the Netherlands. Moreover, A future river discharge scenario was chosen depending on the flooding protection level in Germany. River flooding in Germany leads to an attenuation of the flooding wave that enters the Netherlands. For the safety standards derivation, it was assumed that the differences in the protection levels between Germany and the Netherlands would remain the same in 2050 (Kind, 2011). This consideration led to the capping of the maximum river discharge that enters the Netherlands via Germany, which influenced the magnitude of extreme discharge conditions in the Netherlands.

The flood risk uncertainty assessment via the Monte Carlo analysis (Gauderis et al., 2011) also contains a degree of subjective decision-making. Expert opinion was a relevant component in the definition of the probability distributions around uncertain variables. The results of the Monte Carlo and the scenario analyses supported the decision of defining the safety standards in classes with pattern 1-3-10: maximum failure probabilities equal to 1/10000, 1/30000, 1/100000, which provide a robust classification (Slootjes et al., 2016). For example, the uncertainty in the evacuation fraction during a flooding event resulted in a variability of factor 2 to 3 around the loss of life risk (Beckers et al., 2011), which was accounted for by setting the safety standards with increments of factor 3. A recent uncertainty analysis of the flood safety standards in the Netherlands (Westerhof et al., 2022) shows that expert elicitation remains an important tool for identifying and quantifying the uncertainty within the current safety standards derivation process.

Some of the decision-making processes within the safety standards derivation contain a political or social component. For instance, the basic level of protection was defined by the government as a maximum probability of 1/100,000 per year that an individual will die as a result of flooding (Kok et al., 2017). The selection of this value is mostly associated to a social perception of safety and to governmental policy.

2.1.3. Safety assessment instruments

The safety assessment instruments, WBI for its initials in Dutch (Wettelijk Beoordelingsinstrumentarium), were introduced into legislation along with the current safety standards in 2017 (Ministry of Infrastructure and Water Management, 2016). They consist of the technical methodologies that flood defence managers are legally required to follow when carrying out a safety assessment of a primary flood defence in the Netherlands. Their objective is to provide a standardized process for periodic assessment of all primary flood defences. In this section, the main characteristics of the WBI are discussed. Moreover, the approach in which the WBI accounts for uncertainties is described, with a particular focus on the hydraulic loads. In the remaining of this report, they are referred as WBI, and refer to the safety assessment instruments released in 2017.

Between 2017 and 2023, a first national assessment round was carried out and served as a basis to update the safety assessment instruments (Inspectie Leefomgeving en Transport, 2023). The updated instruments, BOI for its initials in Dutch (Beoordelings-en ontwerpinstrumentarium), have not been officially released in completion (Ministry of Infrastructure and Water Management, 2022). The hydraulic loads for the second national assessment round, starting in 2023, have not been defined yet as significant differences in the calculated water levels were observed after an update of the numerical model (Informatiepunt Leefomgeving, 2024). These differences are currently undergoing investigation to gain more confidence on the hydraulic loads calculation. In the meantime, the hydraulic loads defined in 2017 are being used for the assessment of the flood defences. For this thesis research, the WBI 2017 was considered as the up-to-date safety assessment instruments. It is expected that the BOI 2023 will not contain significant changes regarding the safety assessment methodology compared to the WBI 2017.

Assessment process

The outcome of the assessment process is to determine whether a flood defence complies with the current safety standards, stated as failure probabilities. The calculation of the failure probability follows probabilistic approaches to account for uncertainties in the loads on a flood defence as well as in its strength, as stated in the WBI (Ministry of Infrastructure and Water Management, 2016). The main stages within the assessment process are schematized in Figure 2.2.

The river geometry is schematized in the initial stage within the WBI. Currently, the river bed and floodplain elevations are obtained from the most recent measurement campaigns (De Waal et al., 2014). Then, numerical models are used to compute the hydraulic loads at the flood defences along the river branches in the Netherlands. Several combinations of river discharge and wind conditions are defined to calculate the water levels and wave conditions, and their uncertainty, at the flood defences (De Waal et al., 2018).

The strength of the flood defences is an uncertain variable defined in probabilistic terms. The defences along the river systems are mainly composed of dike structures, whose strength depends on their geometrical configuration, type and quality of cover, and material properties (Jonkman et al., 2016). The loads and the strength of the dikes are integrated into a failure probability via failure mechanisms and a probabilistic model. Some of the main mechanisms include overtopping, macro-instability and piping (Figure 2.1).

Finally, the calculated failure probability of a flood defence is compared against the safety standards. Then, it is determined whether a flood defence needs to be reinforced. The design process for the reinforcement of a dike structure considers a design life in the order of magnitude of 50 years (Kok et al., 2017). This long-term projection is in the same order as that related to the derivation process of the safety standards; therefore, similar uncertainties apply for the calculation of future hydraulic loads and strength of the dike structure.

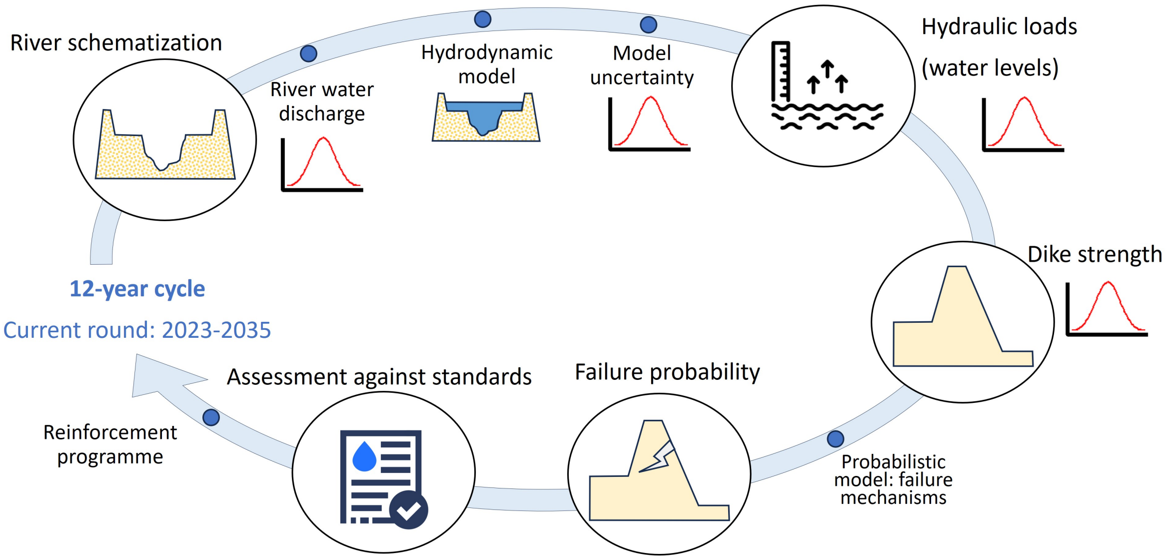


Figure 2.2: Schematized safety assessment process within the WBI

12-year periodic cycle

The assessment period of the WBI has been defined as a 12-year cycle, after which the configuration of the flood defences is updated based on new data and technical findings. Therefore, the uncertainty in the WBI process is related to the variability within 12 years, which is a considerable shorter period compared to the analysis period for the safety standards derivation. As a result, the uncertainties associated to the WBI are essentially different, and can be represented and treated following a different approach.

The safety assessment of a flood defence is based on its situation at the end of the assessment period, which is called the reference date (Kok et al., 2017). Processes such as sea level rise, land subsidence and aging of structures reduce the reliability of the flood defences in time and have to be estimated at the reference date according to the WBI. Limiting the base state of knowledge every 12 years allows to follow probabilistic approaches, since most uncertainty sources can be simplified into single parameters and can be expressed by probability distribution functions. More complex uncertainties such as economic growth and future climate are less relevant within the WBI short-term period than within the safety standards derivation process.

Cost-effective assessment tool

The assessment process of flood defences is time-consuming (Chbab et al., 2015). It involves applying probabilistic methods with conceptually complex foundations at flood defences that span over several kilometers of dike structures with different characteristics. For instance, geotechnical properties vary considerable every few hundred meters, which requires the assessment of a high number of dike sections with overall similar properties (Jonkman et al., 2016). The failure probabilities are therefore calculated at the dike section level for every failure mechanism and further integrated via a system analysis to compute the failure probability of a flood defence. This analysis is computationally-expensive and depends mainly on the number of variables modelled as random variables within the probabilistic model (Slomp, 2022).

Due to this complexity, the WBI aim at developing a cost-efficient procedure for the assessment of flood defences. Within the WBI, it was essential to develop user-friendly tools for more general flood defences managers (Slomp, 2016). This cost-effective feature drove the nature of the WBI, by defining simple procedures when possible and complex processes when required. Moreover, it influenced the way in which uncertainties are accounted for in the WBI, particularly regarding the number of variables to be modelled in a probabilistic, or stochastic, manner.

Dealing with uncertainties

The WBI probabilistic methods take into account a higher number of uncertainties in a physical-based manner than previous methods. It allowed to integrate knowledge on both loads and strength, including their uncertainties, in a more consistent model (Slomp, 2016). For instance, past semi-probabilistic tools were difficult to integrate between different failure mechanisms. In the current safety assessment instruments, different types of uncertainties are considered in the hydraulic loads, flood defences strength, numerical models and statistical assumptions.

Lack of knowledge of some physical processes requires the use of empirical models. For example, the piping failure mechanism (Figure 2.1) is comprised of complex phenomena that cannot be physically modeled; therefore, uncertainty is not modelled around physical processes, but rather around empirical simplifications (Slomp, 2016). As a consequence, a mix of empirical and process-based models are applied to represent different types of uncertainties within the WBI.

In order to deal with uncertainties, stochastic variables were defined within the WBI. Given its cost-effective aim and the computationally-expensive probabilistic models required, the selection of the stochastic variables underwent a thorough analysis (Chbab, 2017a). The number of stochastic variables was minimized, considering only those variables whose effects were deemed to be the most significant to the assessment process. This assessment was based on the existing technical knowledge regarding the uncertain variables; however, not all uncertain variables had been numerically quantified via probabilistic methods, such as the future river bed level. Some stochastic variables considered in the WBI include the river discharge, wind direction and magnitude, and sea level (De Waal, 2018).

Other variables, which had a smaller effect compared to the main stochastic variables or entailed too complex processes, were accounted for in a deterministic manner, instead of as additional stochastic variables (Chbab, 2017a). For example, the uncertainty in the river bed schematization, the bed roughness coefficient and the discharge distribution at river bifurcations were not found feasible to be represented as stochastic variables due to their added complexity in the WBI. Nonetheless, their uncertainty is accounted for in a deterministic manner, as will be discussed next for the hydraulic loads.

Uncertainty in hydraulic loads

Hydraulic loads refer to water levels and wave heights at the location of flood defences. These depend on sea level, river discharge, wind conditions and the hydrodynamic processes at a specific water system. In river-dominated areas, water levels are driven by the upstream river discharge. A hydrodynamic model is used to translate the upstream discharge conditions into hydraulic loads at the location of the flood defences. Figure 2.3 schematizes the process of calculating the hydraulic loads and the associated uncertainties for the river-dominated systems in the Netherlands.

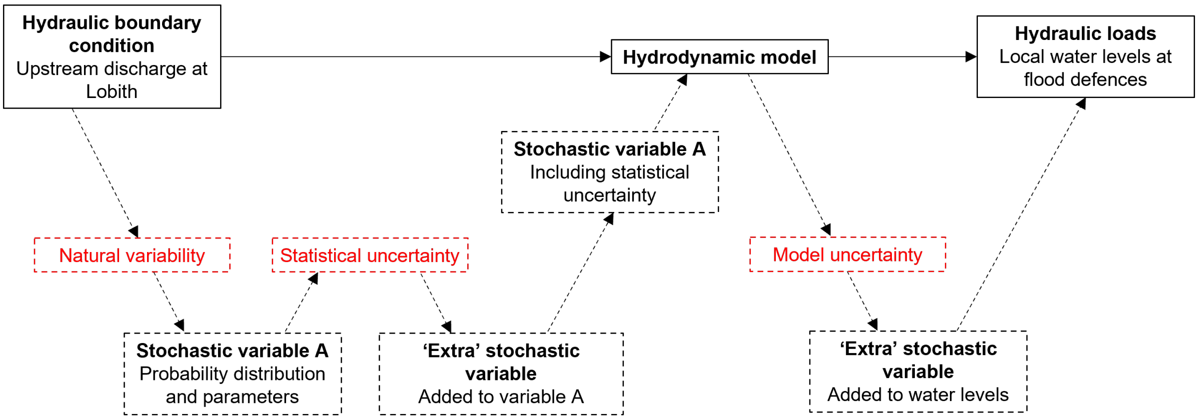


Figure 2.3: Hydraulic loads calculation and uncertainties within the WBI

Within the WBI, three types of uncertainty are considered when calculating the hydraulic loads: a) natural variability, b) statistical uncertainty and c) model uncertainty (Diermanse, 2016). Natural variability refers to the inherent uncertainty of future river discharges. This variable is modelled as a stochastic variable with a probabilistic distribution that describes the probability of occurrence of extreme river discharges. Nonetheless, the selection of a specific probabilistic distribution and its parameters represent another uncertainty source, called statistical uncertainty. This uncertainty is not modelled as an independent stochastic variable, but rather is incorporated into the previous stochastic variable via an integration method (Chbab et al., 2017b). In this method, the statistical uncertainty is first estimated based on the confidence intervals of the extreme river discharges. It is represented by a standard deviation around the discharges and then numerically integrated into the natural variability variable by addition (Geerse, 2015).

The model uncertainty comprises the uncertainties in the transformation process from the upstream discharge condition into local water levels at the flood defences through a hydrodynamic model. The most relevant sources of model uncertainty identified in the WBI include a) uncertainties due to morphological changes under extreme conditions, b) uncertainties due to discharge distribution at bifurcations under extreme conditions and c) uncertainties due to the choice of the calibration approach (Tijssen et al., 2014; Chbab, 2015). The model uncertainty was estimated based on existing hindcast studies, sensitivity studies and expert judgement.

In the WBI, model uncertainty is added as a probabilistic normal distribution, defined by a mean and standard deviation around the local water levels at the flood defences. This implies that it is not modelled as an additional stochastic variable, but incorporated into an existing variable. The mean is defined equal to zero since the model is considered to be well calibrated to the existing hydrodynamic behaviour (Chbab et al., 2017b). Then, the model uncertainty is characterized by a standard deviation around the calculated local water levels at the flood defences.

For the river-dominated Waal, part of the Rhine branches, the standard deviation of the local water levels is currently stated as 15 cm (Figure 2.4). However, it was first estimated at 80 cm based on expert opinion considering morphological changes under extreme discharge conditions, which had not been assessed before (Tijssen, 2014). This value was deemed too large and was then reduced to 15 cm in official documents based on technical arguments and political reasons (Mosselman, 2018). Expert opinion was the main technical tool for the model uncertainty estimation given the large uncertainties in the physical processes under conditions that have not yet been observed. In this uncertain context, non-technical considerations such as elevated reinforcement costs or resistance to setting high-value precedents can play an important role in the political decision-making process.

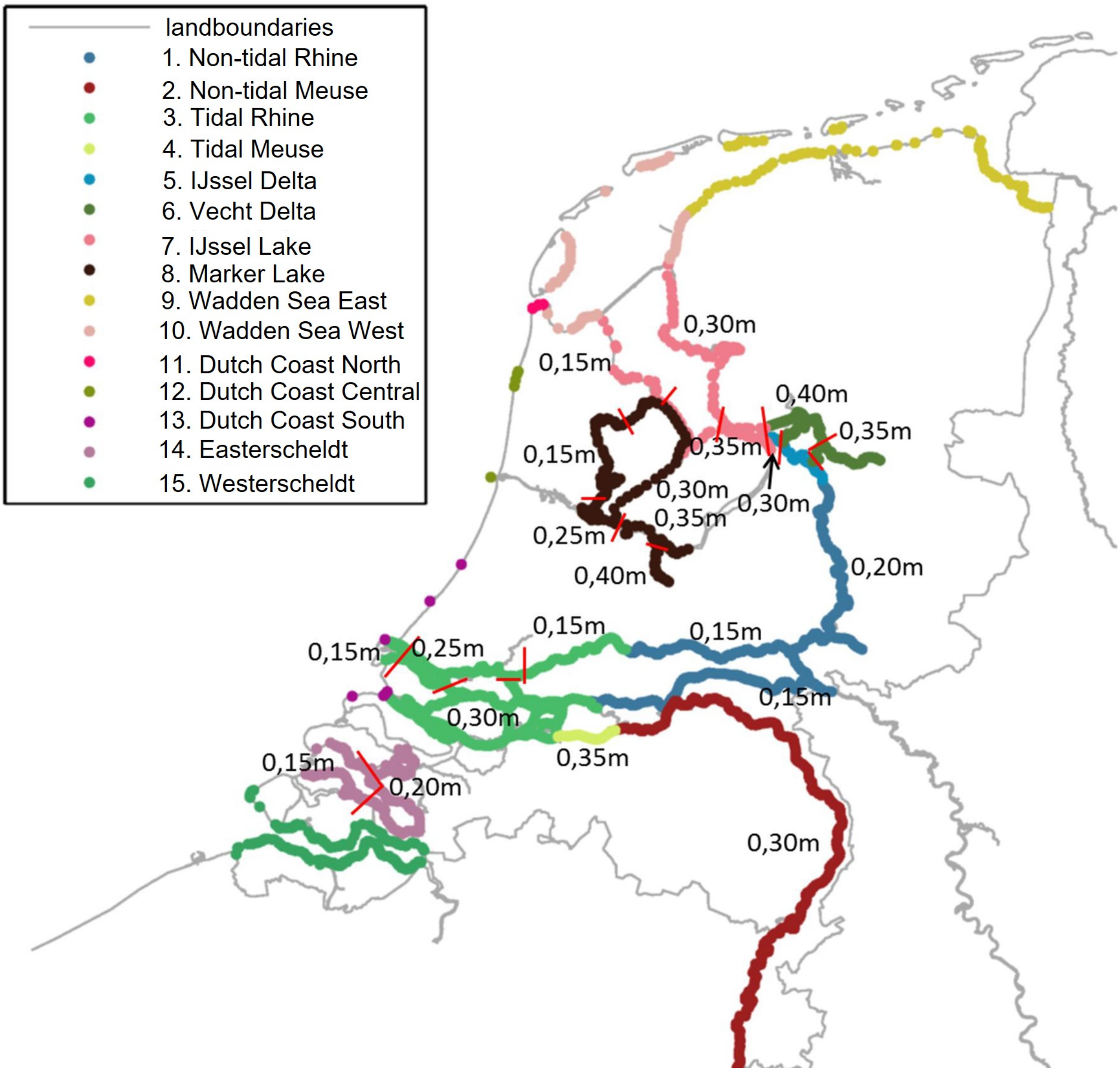


Figure 2.4: Model uncertainty as standard deviation around local water level (Chbab, 2015)

2.2. River morphodynamics in the Netherlands

2.2.1. Main morphological processes in the Rhine River

The Rhine River is a heavily engineered river that flows into the Netherlands via Germany. It enters the Netherlands at its lowermost section under the name Bovenrijn and bifurcates into three branches: Waal, Nederrijn-Lek and IJssel (Figure 2.5). Over the last centuries, the Dutch Rhine has undergone morphological changes driven by human interventions (Ylla Arbós et al., 2021) in addition to natural processes. Morphological changes take place at different temporal and spatial scales (Van Vuren, 2005). Large scale changes include longitudinal profile evolution and morphological evolution at river bifurcations; small scale changes, bedform evolution and local river bed erosion and sedimentation. This section describes these morphological features in the Dutch Rhine.

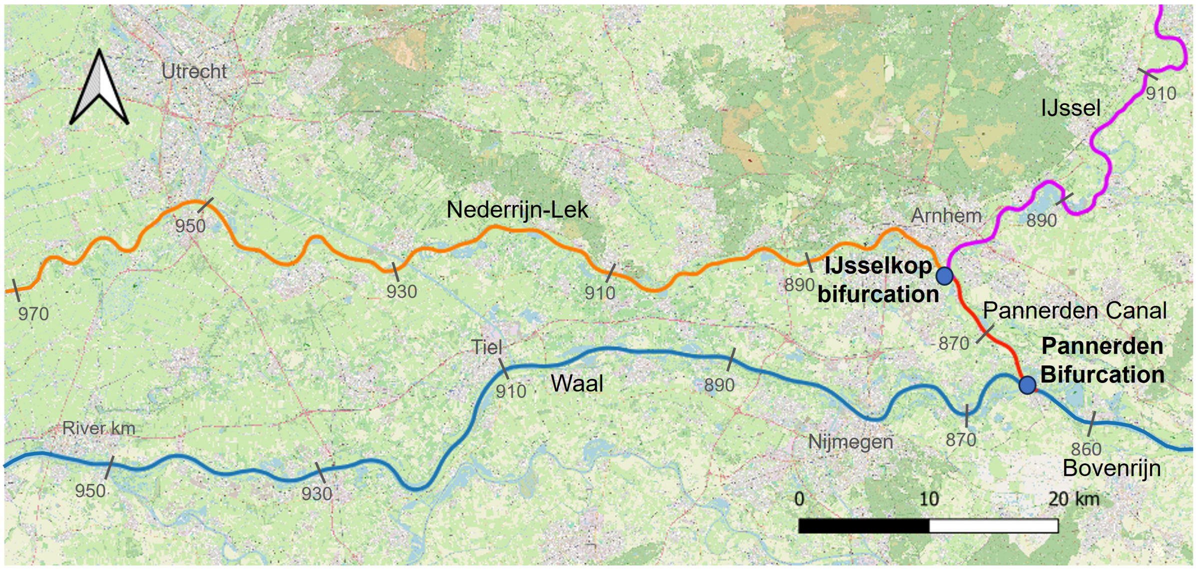


Figure 2.5: Rhine River and its main branches in the Netherlands (Map source: OpenStreetMap)

Longitudinal profile evolution

The past and ongoing longitudinal profile evolution in the Dutch Rhine has been associated to past channelization, sediment management practices and the 'Room for the River' interventions (Chowdhury et al., 2023; Ylla Arbós et al., 2021; Van Vuren, 2005). In the 19th and early 20th centuries, channelization measures such as river straightening, bank stabilization and meandering cut-offs have been applied in the Rhine for navigability and flood management purposes (Van Vuren, 2005). This resulted in domain-wide river bed tilting, with an overall reduction of the bed slope (Ylla Arbós et al. 2021). The incision rates in the Dutch Rhine were highest in the early 1900s and have decreased with time. Since the 1990s, the bed level has been stable in the Bovenrijn, and the incision rates have reduced in the upper and middle Waal. In the lower Waal, the bed level has been stable or aggraded. Around river km 930 in the Waal, a bed aggrading trend between 2005 and 2020 has been identified and associated to large-scale past channelization (Van Denderen et al., 2022).

Dredging and nourishment have been main river management techniques in the Rhine River. In the Netherlands, large-scale dredging campaigns took place in the 19th and 20th centuries, mostly without regulation (Van Vuren, 2005). Chowdhury et al. (2023) show that intensive dredging during the 1980s has led to erosion in the Bovenrijn and in the Waal. Since 1991, dredging is allowed for navigability purposes as long as the sediment is returned to the river system. Sediment nourishment has taken place since 1989 in the German part of the Rhine in order to reduce river bed incision (Ylla Arbós et al., 2021). Within the Netherlands, nourishment pilot campaigns have been carried out at the section upstream of the Pannerden Bifurcation in 2016 and 2019.

The program Room for the River is the most recent major intervention program in the Netherlands, which took place between 2007 and 2018 (Ylla Arbós et al., 2021). It has the purpose of increasing channel conveyance capacity by lowering of floodplains, removal of obstructions, construction of secondary channels, among other measures (Silva et al., 2001). These interventions affect the water and sediment transport fields and distribution over the main channel and floodplain, which triggers morphological processes (Van Vuren et al., 2015). The increased channel conveyance leads to lower flow velocities, which reduces the large-scale bed degradation in the Waal. These morphological changes take place over the length of the interventions and at shorter temporal scales than those due to large-scale channelization (Van Denderen et al., 2022).

Large-scale bed level changes take place via bed aggradation and degradation waves. These adjustment waves originate from the difference between sediment supply and sediment transport capacity, and migrate downstream (Chowdhury et al., 2023). In the Waal, past channelization has been associated to adjustment waves with wavelengths greater than 9 km; whereas localized interventions, to wavelengths between 300 m and 9 km (Van Denderen et al., 2022). Despite their different spatial scales, they have been found to cause bed level variations in the same order of magnitude. Around river km 930, a bed level variability between +/- 20 cm has been identified due to the migration of bed level waves with wavelengths between 300 m and 9 km (Van Denderen et al., 2022). The construction of a side channel in 2015 increased the bed level variability at the upstream and downstream ends of the side channel and led to aggradation of the main river channel.

Morphodynamics at bifurcations

In the Netherlands, river bifurcations play a major role as they determine the amount of water and sediment that is distributed over its branches (Van Vuren, 2005), thus influencing all river functions in the downstream branches. The water and sediment distribution over the bifurcates depends on the conveyance capacity of each branch and on local three dimensional characteristics such as the bifurcation angle, the transverse bed slope and planform upstream (Chowdhury et al., 2023; Schielen and Blom, 2018).

Chowdhury et al. (2023) studied how the Pannerden and the IJsselkop bifurcation of the Rhine River in the Netherlands have evolved in response to interventions and natural changes over the last half century. They showed that the Waal branch has taken an increasingly discharge fraction over the last two decades. This was attributed to the rapid succession of the peak flow events in 1993-1995-1998, which triggered local sedimentation over the Pannerden Canal and a higher erosion rate in the Waal branch compared to the other bifurcate. This behaviour resembles an unstable bifurcation state in which one of the bifurcates dominates over the other until the latter eventually closes (Schielen and Blom, 2018).

Bed degradation waves have been found to originate from the occurrence of peak flows at the Pannerden bifurcation (Chowdhury et al., 2023). These waves travel at celerities between 0.6 and 1.7 km/year and enhance the degradation rate of the upper Waal due to past channelization. The future morphological evolution of the bifurcation may be strongly impacted by more frequent peak flows associated with climate change.

Small scale morphodynamic features

At small scales, river morphology is defined by bedforms: disturbances at the river bed following sediment transport processes. In the Rhine, they consist of ripples and dunes, whose geometry depends on the grain size of the bed material, the water depth and the flow velocity (Van Vuren, 2005). Dune-like bedforms in the Waal have been associated to wavelengths smaller than 300 m (Van Denderen et al., 2022). Smaller bedforms have been identified in the upper end of the Waal due to coarser bed material that is less mobile.

Dunes adapt their shape to small temporal fluctuations in water discharge, which triggers degradation and aggradation waves that migrate along the river channel (Van Denderen et al., 2022). The bed level variation due to bedforms averages out in time and at larger spatial scales. However, the geometrical configuration of bedforms affects flow resistance in a river, therefore having an impact on navigability, flood risk and other river functions (Van der Mark, 2009).

Sediment degradation occurs locally around hydraulic structures such as groynes and fixed layers that induce abrupt velocity gradients. The reduced transport capacity over these structures leads to bed erosion immediately downstream (Van Denderen et al., 2022). In the Netherlands, groynes have been extensively constructed for channelization purposes and resulted not only in local scour holes at the tip of the groynes, but also on deposition areas downstream of them (Van Vuren, 2005). Local erosion may generate stability problems at hydraulic structures and dikes, whereas deposition areas may hinder navigability.

2.2.2. Effects of morphology on flood safety

River morphodynamics impacts flood safety by imposing dynamic conditions on the river system, which affects the loads and resistance of a flood defence. Over the last decades, the impact of river morphodynamics on flood safety has been increasingly investigated (Vázquez-Tarrío et al., 2024). During flood events, sediment transport processes can generate bank erosion, channel avulsions and other abrupt planform changes that pose risks to people and infrastructure. Moreover, bedform migration and evolution during flood events influence the flow resistance and therefore the water levels (Van der

Mark, 2009). In the long-term, sediment transport can lead to changes in the conveyance capacity, particularly considering that the morphological changes are expected to occur in response to climate change (Vázquez-Tarrío et al., 2024). The sediment load carried during flood events can also affect the damage on buildings, infrastructure and people, which can increase flood risk.

In this section, the main implications of river morphology on flood safety are described for the river system in the Netherlands. Figure 2.6 shows a summary of the main morphological processes and related physical phenomena. Considering that the river system in the Netherlands is highly engineered and channelized, morphological changes on the planform are neglected. Following the risk-based approach terminology in the Dutch flood safety framework, morphological physical processes are linked to an impact on the loads at the flood defences, their strength and the flooding damage estimation.

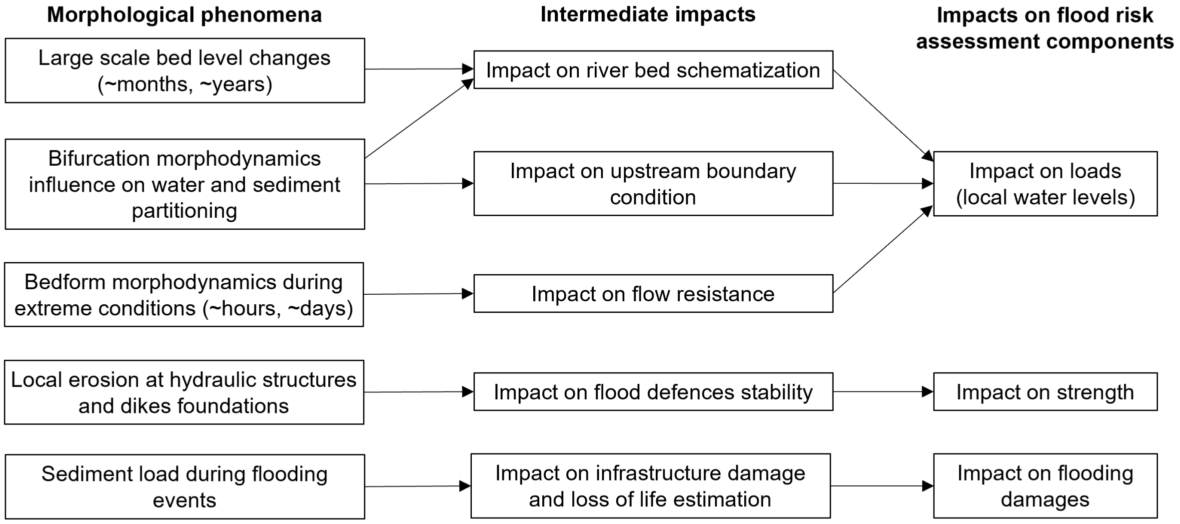


Figure 2.6: Implications of river morphology on flood safety

Large-scale bed level changes

Large-scale bed level changes are defined in the order of hundreds of meters to a few kilometers, where smaller features such as bedforms are averaged out. Large-scale changes are associated to long-term morphological periods, as it takes a longer time for sediment to be transported within these spatial scales. Time scales vary from several months to years and decades, depending on river controls such as the upstream discharge, the input and composition of the sediment and the downstream water level (De Vriend, 2015). Therefore, large-scale bed level changes are representative of the mean river morphological response.

River bed sedimentation is a large-scale morphological features that can pose negative impacts on flood safety. Sedimentation can lead to a reduction in the channel conveyance capacity (Ahrendt et al., 2022), inducing higher water levels for the same discharge. Therefore, the loads on a flood defence could be increased by river bed sedimentation. In the Rhine branches, bed level sedimentation has been observed in the lower Waal as a response to sea level rise and localized human interventions (Van Denderen et al., 2022; Ylla Arbós et al., 2021, Blom, 2016; Van Vuren, 2005). Current future plans in the Waal consider river interventions for the maintenance and raising of the river bed to counteract the ongoing erosion trend (Ministry of Infrastructure and Water Management, 2023). These measures could increase the future relevance of large-scale bed level changes in the upper Waal as they would lead to higher water levels compared to the situation in which the bed erosion trend continues.

Discharge partitioning at bifurcations during extreme conditions

During extreme discharge conditions, bifurcations determine how much water discharge is distributed over the bifurcate, thus defining their upstream boundary conditions and the hydraulic loads at the flood defences along them, see Section 2.2.1. The discharge partitioning fraction is an uncertain parameter that varies every year depending on the morphodynamic characteristics of the branches around the bifurcation and complex two and three dimensional sediment and flow patterns (Chowdhury et al., 2022). The water discharge partitioning at the Pannerden bifurcation into the Waal has been observed to vary between 60 to 75 % in the period 1970 - 2020 during high flow events. Moreover, the partitioning under design conditions not yet observed is unknown as the morphological processes are highly uncertain (Mosselman, 2012).

Over a longer period of time, erosion waves that originate at the bifurcation during peak flows pose additional negative impacts on flood safety. Successive peak flows have been found to trigger an increasing trend in the discharge fraction flowing into the Waal, see Section 2.2.1. This slower change due to bifurcation morphodynamics can lead to higher hydraulic loads in the flood defences of the Waal, which is not accounted for in the current flood risk management (Chowdhury et al., 2022).

Bedforms during extreme conditions

At a small-scale, bedforms dynamics can have a considerable impact on the hydrodynamics and on flood safety, as they influence the flow resistance (Van der Mark, 2009). During extreme conditions, bedforms undergo changes in size which can increase flow resistance and induce higher water levels. The flow resistance has been estimated to vary between +/- 50% due to the uncertainty in bedform evolution at extreme conditions, which would correspond to a variability in the design water levels in the order of 1 m in the Waal (Mosselman, 2012; Van der Mark, 2009).

Local erosion at hydraulic structures

Local erosion may generate stability problems at hydraulic structures, as described in Section 2.1.1. These can be produced not only by the construction of the structure itself, but also due to external causes. For instance, river-wide incision may cause weakening of hydraulic structures foundations (Ylla Arbós et al., 2021). Interventions such as floodplain lowering may also induce erosion processes at nearby hydraulic structures (Van Vuren, 2005). Overall, these can reduce the strength of a flood defence and increase flood risk.

Damages due to sediment load during flooding events

The sediment load transported in the flooding wave can increase flood risk due to increase damages on infrastructure and people (Vázquez-Tarrío et al., 2024). For example, the suspended sediment load, of major importance in alluvial rivers such as the Waal (Van Vuren, 2005), can lead to sediment accumulation on roads and other infrastructure that can hinder rescue and reconstruction efforts after flood peaks. These effects can lead to higher economic damage and loss of life estimations when considering sediment transport within the flood wave. Considering that the mortality and damage functions have been found to be two main sources of uncertainty in the current flood safety standards derivation process (Westerhof et al., 2022), the enhanced damages due to sediment load could play a significant role within the flood risk assessment in the Netherlands.

2.2.3. Prediction of future morphological changes

Previous sections have described the dynamic nature of river morphology and its impacts on flood safety in the Netherlands. This section aims at describing the main methods for predicting future morphological changes. These are divided in two main categories: a) based on morphodynamic modelling and b) based on observations. The former may be further divided into deterministic and stochastic modelling.

Deterministic morphodynamic modelling

Morphodynamic models are process-based models in which sediment transport processes are coupled with a hydrodynamic module to compute the morphological changes via the solution of the equations of continuity and momentum of water and sediment (Van Vuren, 2005). The model requires morphological inputs such as the upstream sediment inflow, number of sediment fractions, grain size of bed material and sediment relative density. Moreover, a sediment transport model is adopted, which defines thresholds for sediment motion, as well as sediment flow as a function of flow velocity.

Morphodynamic models are complex given limited knowledge on sediment transport processes and given limited measurements available for calibration and validation (Vázquez-Tarrío et al., 2024). However, they represent an important tool for assessing the long-term and large-scale morphological effects of river interventions, such as those developed within the Integrated River Management Programme in the Netherlands (Ministry of Infrastructure and Water Management, 2023; Chavarrias et al., 2020).

In a deterministic model, variables are defined as single parameters representing the best estimate for a given physical process. Calibration takes place in order to estimate the main uncertain variables based on past measurements. Sensitivity analysis complement a deterministic model by assessing how much the results deviate from the best estimate when varying an input parameter of the model. Ylla Arbós et al. (2023) studied the morphological response to different climate change scenarios in the Netherlands. The incorporation of multiple scenarios, as a sensitivity analysis, provides an idea of the variability in the morphological response.

Stochastic morphodynamic modelling

Stochastic models can consider input parameters as random variables and can characterize their variability in probabilistic terms. A stochastic morphodynamic model is able to indicate the range of possible morphodynamic states and their probability of occurrence (Van Vuren, 2005). Given the high uncertainty involved in morphological processes, these models provide insights into the possible responses of a river system.

Stochastic morphodynamic models face two challenges: a) they add complexity to the morphodynamic model by incorporating probabilistic methods and b) they require large computational effort and time to be carried out. Additional steps in the modelling design phase included the choice of a stochastic model, for example, via Monte Carlo simulations, and the choice of which and how many random variables are considered (Van Vuren, 2005). Despite its drawbacks, stochastic morphodynamic modelling has been used to investigate the impacts of river morphodynamic uncertainty on river restoration works, river dredging and flood protection in the Netherlands (Van Vuren et al., 2016; Huthoff et al., 2010).

Arkesteijn et al. (2021) developed an efficient approach to calculate the mean river response under stochastic river controls without the necessity of computational expensive models. The results following this approach resemble the mean outcome of a fully probabilistic model; however, this approach does not provide information regarding the uncertainty range of the morphological response.

Based on observations

Morphological changes can also be analyzed based on past observations. In the Netherlands, Van Vuren (2005) carried out an analysis of the bed level variability in the Dutch Rhine based on bathymetric observations between 1990 and 2000. Despite the short record, the analysis yielded similar results for the bed level variability when compared to fully stochastic morphodynamic modelling results.

Past bed level observations have also been complemented with probabilistic methods to estimate future changes. For example, Oliver et al. (2018) induced future morphological changes from observed sedimentation trends in the Upper Koshi River in Nepal. Based on the past river bed behaviour, statistically properties were defined for the yearly bed level increase and future bed level changes were probabilistically estimated.

Ahrendt et al. (2022) applied the specific gage analysis method to infer bed level changes based on trends in stage-discharge measuring stations. In this method, channel conveyance capacity is inferred from shifts in stage-discharge relationship at measuring stations. This method does not require direct bed level measurements, which is an advantage in river systems with less regular monitoring. However, the results are less representative for river sections that are located away from the measuring stations.

These methods do not require morphodynamic models, which greatly reduces the complexity of prediction morphological changes. However, they are limited by the amount of available data, and physical processes are not explicitly considered in these approaches. As a consequence, the overall representativeness of its future predictions is less clear, which makes these methods less reliable for long-term predictions.

2.2.4. Uncertainty in river morphodynamics

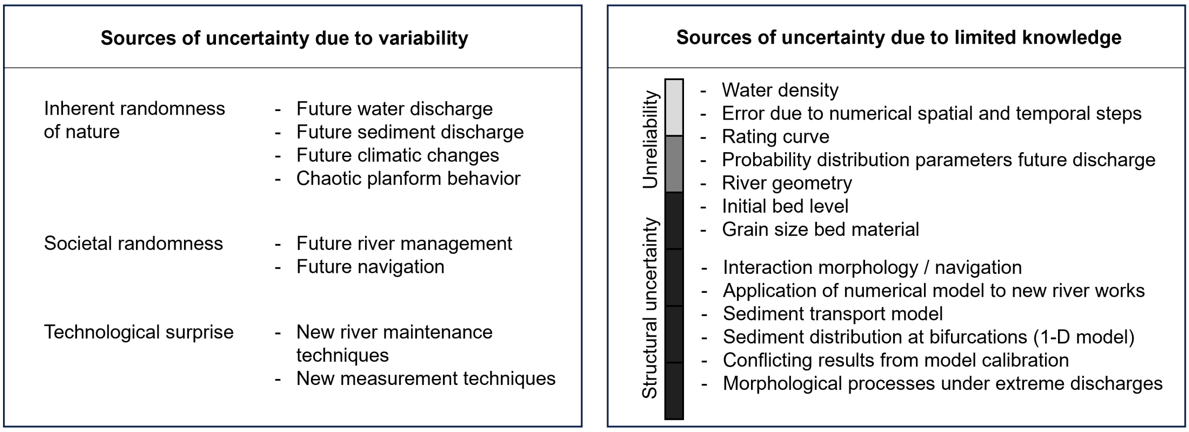
River morphology is constantly adapting to natural variability and human interventions according to complex physical processes. These characteristics attribute large uncertainties to the prediction of future morphological changes. Van Asselt (2000) classified these uncertainties into ones due to inherent variability and others due to limited knowledge. Limited knowledge can be caused by inexactness, lack of measurements, practically immeasurable quantities, processes not observed and indeterminacy of natural processes.

In river morphodynamic models, uncertainties can be introduced via model schematization, boundary conditions, initial conditions, model parameters and model equations (Van Vuren, 2005). Moreover, these uncertainty sources are time and space dependent with highly non-linear interrelations (Van der Klis, 2002). In this section, uncertainty sources and their relevance in flood safety are described under the framework in the Netherlands.

Uncertainty sources

Van der Klis (2002) and Van Vuren (2005) carried out extensive research on the uncertainty of river morphodynamics, their categorization and quantification. Van der Klis (2002) identified uncertainty sources such as future water discharge, future sediment discharge, future climate change, future river management, river geometry and sediment transport models. Figure 2.7 shows the full list of uncertainty sources identified by Van der Klis (2002).

Van der Klis (2002) assessed the relative importance of uncertainty sources, concluding that future river discharge is one of the relative important uncertainties in river morphology. The hydraulic roughness and the grain size of bed material were also found to be relatively important uncertainty sources. Van Vuren (2005) carried out a similar analysis, in which it was found that river discharge, the hydraulic roughness and the parameters of the sediment transport formula were the most relevant uncertainty sources.



Sources of uncertainty due to variability

Inherent randomness of nature	- Future water discharge - Future sediment discharge - Future climatic changes - Chaotic planform behavior
Societal randomness	- Future river management - Future navigation
Technological surprise	- New river maintenance techniques - New measurement techniques

Sources of uncertainty due to limited knowledge

- Water density
- Error due to numerical spatial and temporal steps
- Rating curve
- Probability distribution parameters future discharge
- River geometry
- Initial bed level
- Grain size bed material

- Interaction morphology / navigation
- Application of numerical model to new river works
- Sediment transport model
- Sediment distribution at bifurcations (1-D model)
- Conflicting results from model calibration
- Morphological processes under extreme discharges

Figure 2.7: Examples of uncertainty sources in river morphodynamics (Van der Klis, 2002)

Relevance of uncertainty sources in flood safety

The flood safety framework in the Netherlands can be represented by two main elements: a) safety assessment every 12 years and b) safety standards derivation every 50 - 100 years. The relevance of morphological uncertainties may be different for short-term, medium-term and long-term predictions (Van Vuren, 2005). Therefore, it is adequate to classify the uncertainties under the two time-scales considered in the current flood safety framework.

Figure 2.8 shows the uncertainty sources that have been identified as most relevant for flood safety in the Netherlands. These uncertainties are also distinguished as inherent uncertainties and epistemological uncertainties, following the classification from Van Gelder (2000). Inherent uncertainties are intrinsically uncertain due to nature. Epistemological uncertainty refers to the imperfection or incompleteness of model representations (Van Vuren, 2005). Epistemological uncertainties are more complex than inherent uncertainties since they cannot be represented by a single parameters, but rather comprise several relations and parameters within a model.

Future water discharge has been the most relevant uncertainty source found in the literature. The impact of its natural variability has been assessed in several river functions, including flood risk. In the Netherlands, uncertainty of the discharge partitioning at the bifurcations play a major role, since they determine the upstream boundary condition of the bifurcates (Chowdhury et al., 2023; Ahrendt et al., 2022).

The sediment transport model entails large epistemological uncertainties, given the high complexities in sediment dynamics. Moreover, related parameters such as grain size bed material and hydraulic roughness have been found to be relevant sources of uncertainty (Van der Klis, 2002; Van Vuren, 2005). They also influence bed coarsening in the Dutch Rhine, which affects the mobility and sediment dynamics of the river bed material (Van Denderen et al., 2022; Ylla Arbós et al., 2021). During extreme conditions, bedform dynamics are a considerable source of uncertainty which affect flood safety (Mosselman, 2012).

In a time span of 50 to 100 years, some epistemological uncertainties increase their relative relevance. For instance, future climate change has been found to have non-neglectable effects on river morphology in the Netherlands (Ylla Arbós et al., 2023). Furthermore, the bifurcation morphological evolution in the Netherlands has been found to be susceptible to high flows (Chowdhury et al., 2023), which could trigger a redistribution of discharge in the Rhine branches. Lastly, river management is intensively practiced in the Netherlands; future intervention programs pose uncertainties into future river morphology and flood safety.

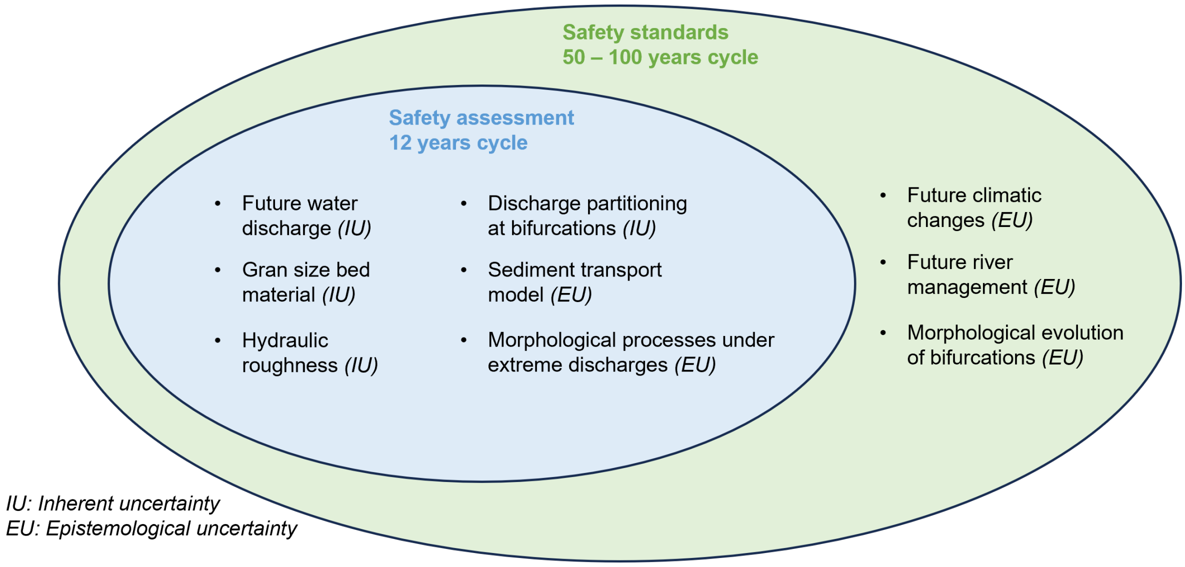


Figure 2.8: Uncertainty sources in river morphodynamics most relevant for flood safety in the Netherlands

3

A flood safety framework incorporating river bed level variability in the Netherlands

3.1. Introduction

This chapter reviews existing methods for incorporating bed level changes into flood risk assessment, discusses the morphological considerations within the current flood safety framework in the Netherlands, and proposes an approach for incorporating bed level changes into this framework. The focus lies on incorporating large-scale bed level changes into flood safety, as they are assumed not to have negative implications on flood safety in the current framework. Large-scale bed level changes are not modelled within the current framework; however, they could have negative implications on the lower river sections, see Section 2.2. Moreover, past bed level measurements and recent long-term morphodynamic studies of the Dutch Rhine provide sufficient inputs for quantifying the impacts of large-scale bed level changes on flood safety.

3.2. Existing flood risk assessments methods including bed level changes

As described in Section 2.2, bed level changes due to morphological processes can increase flood risk. Previous studies have analyzed the impact of large-scale bed level changes on flood risk assessments following different methodologies (Hiemstra et al., 2022; Dysarz, 2020; Oliver et al., 2018; Pender et al., 2016). Other studies have focused on assessing the impact of sediment transport during flood events on the water levels (Liu et al., 2022; Asinya and Alam, 2021; Reisenbüchler et al., 2019; Nones, 2019). The latter are most relevant in mountain streams and torrents, where the mobilization of large sediments can lead to debris flows that strongly influence the flow properties during the flood event (Vázquez-Tarrío et al., 2024). In lowland rivers such as the Dutch Rhine, large-scale bed level changes associated to time scales from years to decades are most relevant.

Most studies on large-scale bed level changes have quantified their impact on the design water levels or inundation maps associated to a given exceedance probability. A smaller number of studies have further quantified their impact on the failure probability of the flood defences, incorporating its strength, and on the flooding economic damages (Oliver et al. 2018; Neuhold et al., 2009). In the latter, the strength of the flood defences and the damage functions are assumed independent from bed level changes. Therefore, the impact of bed level changes is quantified directly on the hydraulic loads, which are then propagated to other components of the flood risk assessment.

The main differentiating features between the existing studies reviewed here are the methods for estimating future bed level changes (Table 3.1) and how these are used to quantify their impact on the hydraulic loads. In the following sections, these methods are analyzed, with a focus on how they account for uncertainties in future bed level changes.

Morphodynamic modelling based	Observations and measurements based
Deterministic modelling	From bed level measurements
Single simulation	From gauging station trends
Multiple scenarios	From bed level measurements and probabilistic methods
Stochastic modelling	
Fully probabilistic	
Mean stochastic response	

Table 3.1: Classification of morphodynamic approaches for future bed level predictions

3.2.1. Methods for incorporating bed level changes based on morphodynamic modelling

Section 2.2 presents a general description of morphodynamic models and their main limitations. Both deterministic and stochastic morphodynamic models have been used to quantify large-scale bed level changes from 5 to 50 years in the future (Dysarz, 2020; Pender et al., 2016; Van Vuren, 2005). Stochastic models focused on resampling techniques to synthesize different river discharge time series sequences equally likely to occur. Different sediment transport formulas have also been assessed as scenarios in addition to the previous resampling technique (Dysarz, 2020).

Dysarz (2020) analyzed the impact of large-scale bed level changes after 6 and 12 years on flood safety in a lowland section of the Warta River in Poland. Multiple future bed level changes were quantified with a morphodynamic model, accounting for uncertainty in the river discharge time series and in the sediment transport formulas. All the calculated bed level configurations were evaluated with a hydrodynamic model to quantify the impacts on the water levels. It was found that future bed level changes are highly variable in space and time. At specific cross sections in the river, the design water levels can vary within a range of 0.5 m for a given sediment transport formula, and within a range of 2 m for multiple sediment transport formulas. This translated into an overall variability in the inundation area by +/- 15% compared to the fixed-bed assumption.

Van Vuren (2005) applied probabilistic morphodynamic models to quantify the impact of bed level variability, due to short-term discharge variability, on the design water levels in the Dutch Rhine according to the previous flood safety framework. All the future bed level configurations were assessed under flooding events by applying a hydrodynamic model. It was concluded that long-term bed level changes have an effect in the order of 0.05 - 0.10 m in the computed design water levels within a period of 20 years of morphological changes. The upper Waal showed lower design water levels in the order of 0.06 m, whereas the lower Waal showed higher design water levels in the order of 0.02 m compared to the fixed-bed assumption. This translated into a decrease and an increase of the exceedance probability of the flood event from 1/1250 to 1/1450 in the upper Waal and from 1/1250 to 1/1200 in the lower Waal, respectively. The results are consistent with the river bed tilting trend in the Waal, where degradation is observed in the upper sections; and sedimentation, in the lower sections. These effects were found to be small in absolute terms, but relatively significant compared to the centimetre-accuracy of the hydraulic loads within the safety assessment process in the Netherlands (Van Vuren, 2005).

Pender et al. (2016) analyzed the impact of long-term bed level changes on the design water levels in the Caldew River in England. A morphodynamic model was used to compute future bed level changes after 50 years, considering variability in the river discharge time series sequencing. Pender et al. (2016) introduced a method for defining future minimum and maximum river bed configurations, which used the envelopes of the bed level changes from all the morphodynamic modelling results. The objective of this method was to reduce the number of simulations required in the hydrodynamic model by providing a single conservative scenario. However, this method does not provide a physical meaningful representation of the morphological processes, as the sediment mass is not conserved. Pender et al. (2016) calculated that the design water levels varied between 0.85 - 1.85 m along the river reach when considering the maximum bed level envelope, and between 0.25 - 0.48 m when considering all the bed level configurations from the morphodynamic model. This shows that the use of a maximum envelope of the bed level changes may lead to over conservative results.

3.2.2. Methods for incorporating bed level changes based on observations and measurements

Previous flood risk studies have incorporated future bed level changes based on observations and measurements, without requiring the use of morphodynamic models. These methods have been used to estimate bed level changes mainly in the short time, up to 5 years into the future (Oliver et al., 2018; Lane et al., 2007), but also in the long term, up to 30 years into the future (Hiemstra et al., 2022). Bed level measurements have been analyzed directly, via probabilistic techniques or as input for defining trends in the bed level changes.

Lane et al. (2007) calculated the flood inundation under two bed level configurations measured 16 months apart in the Wharfe River in England. No uncertainties in the morphological response were accounted for as this study focused on past bed level measurements, which are representative of a single realization of all the possible morphological responses. It was found that river bed sedimentation during the 16-month period led to an increase in the inundation area of 5.7%. This was compared to the isolated impact of increased precipitation due to climate change, which led to an increase in the inundation area of 12.2% and 14.7% in the years 2050 and 2080, respectively. This shows that river bed sedimentation can have significant negative implications on flood safety compared to long-term climate scenarios.

Van Vuren (2005) analyzed the bed level variability in the Dutch Rhine based on a bathymetric database, yearly bed level measurements during 10 years, and compared it to the computed stochasticity of a fully probabilistic morphodynamic model. The results showed that the bed level variability, expressed as the standard deviation of the bed levels, from bathymetric data averaged over the Waal River domain is approximately 0.09 m, whereas the variability obtained from a fully probabilistic model varies between 0.11 and 0.18 m. This shows that yearly bed level measurement records can be used to estimate the variability in the morphological response over a relatively large period of time under the assumption that the dataset is homogeneous. This analysis can be extended to assess the variability in the design water levels given the variability in the bed level measurements under the same assumption.

Hiemstra et al. (2022) assessed the impact of long-term bed level changes and climate change on the design water levels based on two scenarios for the river bed profile of the upper Waal in 2050. One scenario represents the ongoing incision trend in the upper Waal, whereas the other scenario considers the natural stabilization (bed incision stops) of the bed level due to processes such as coarsening of the bed surface sediment and sea level rise. The bed level configurations of both scenarios were not obtained directly from measurements or morphodynamic modelling results, but were defined based on them. The bed level was estimated to erode by approximately 0.5 m over the upper Wall in the ongoing incision scenario. It was found that, in the upper Waal, the increased discharge due to climate change has a larger impact on the design water levels, in the order of 0.40 m, compared to the impact of long-term river bed changes, in the order of 0.10 m.

Oliver et al. (2018) applied a different method for estimating future bed level changes within a flood risk assessment in the upper Koshi River in Nepal. Yearly bed level changes were defined with a probabilistic distribution based on observations and morphological studies. Then, future bed level changes were resampled every year from this probabilistic distribution for a total of 5 years. Although this method could yield stochastic results, the sediment mass conservation is not ensured and the physical morphodynamic processes are not represented.

3.2.3. Summary of existing morphodynamic modelling approaches

Different approaches for incorporating bed level changes into flood risk assessments show a trade-off between simplicity and representativeness. In general, morphodynamic modelling based approaches are more representative but less simple to apply, whereas observations based approaches fall on the opposite spectrum (Figure 3.1). This categorization should be analyzed in a dynamic manner, since the relevance of morphological processes vary greatly depending on the time scale. For instance, trends inferred based on observations may be as representative as single morphodynamic models in the short-term future, but less representative in the long-term future.

It can be concluded that most morphodynamic models incorporated into flood risk assessments quantify the uncertainty in the future river discharge sequencing via stochastic techniques. However, other uncertainty sources in river morphodynamic models, such as the sediment transport formulas, are quantified via scenarios rather than via stochastic methods given their complexity. Furthermore, the bed level variability in the recent past has been analyzed to infer bed level changes in the near future and quantify its impact on flood safety.

In the Dutch Rhine, it has been calculated that future bed level changes will lead to a decrease and an increase in the design water levels in the upper and lower Waal, respectively (Van Vuren, 2005). River discharge amplification due to climate change has been found to have a higher impact on the hydraulic loads compared to the impact from long-term bed level changes in the upper Waal (Hiemstra et al., 2022). Lastly, yearly bed level measurements have been successfully used to estimate the variability in the bed level changes when compared to the results from fully probabilistic morphodynamic models of the Waal.

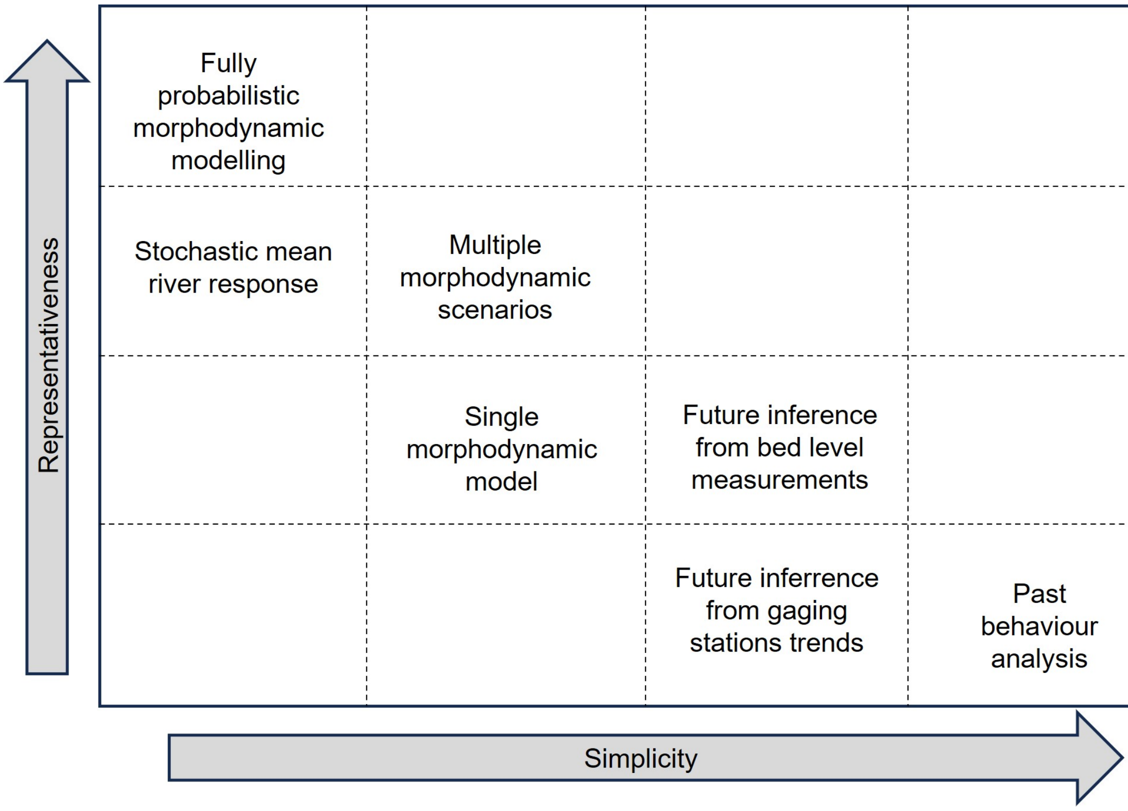


Figure 3.1: Evaluation of morphodynamic approaches based on their representativeness and simplicity

3.3. Morphological considerations in the current flood safety framework in the Netherlands

3.3.1. Bed level as a potential stochastic variable

The river bed level is not considered as a stochastic variable within the current flood safety framework in the Netherlands; however, it was qualitatively assessed as a potential one (see Section 2.1.3). It was found to be too complex to be added as a stochastic variable and not significantly relevant compared to other variables (Chbab, 2017a). These considerations are discussed in the following paragraphs.

On the one side, variable bed level configurations would lead to too many possibilities to calibrate and validate the hydrodynamic model (Chbab, 2017a). Nonetheless, it is possible to incorporate morphodynamic models to calculate future bed level changes and their associated hydraulic loads. Following this approach, an additional calibration step is required for the sediment transport model and its parameters; however, only one initial bed level configuration has to be calibrated. Furthermore, past bed level measurements can be incorporated into hydrodynamic models considering that the observed bed level changes are equivalent to morphodynamic modelling results. Following this approach, a calibration for sediment transport processes is not required; however, downstream boundary conditions may change due to the effect of bed level changes on stage-discharge relationships (Hiemstra et al., 2022;

Van Vuren, 2005). This may be accounted for by adjusting the stage-discharge relationships based on observed bed level trends (Hiemstra et al., 2022) or by setting the downstream boundary condition far away from the area of interest (Pender at al., 2016; Lane et al., 2007).

On the other side, bed level uncertainty was not found to be significantly relevant compared to other stochastic variables, such as the future river discharge (Chbab, 2017a). Overall, future river discharge uncertainty has a higher impact on the hydraulic load than bed level uncertainty; however, it has been found that the latter can become as relevant as the former after unusually large storm or sediment-supply events (Ahrendt et al., 2022). The occurrence of successive peak flows can lead to increased flood risk at the areas where sediment is deposited during the first flood events and is not redistributed before the occurrence of the following flood events. In the Dutch Rhine, an increasing trend in the water discharge partitioning at the Pannerden bifurcation has been attributed to successive peak flow events (see Section 2.2.1). Therefore, bed level changes can affect future discharge conditions at bifurcation systems, thus affecting the main stochastic variable of the hydraulic loads. Moreover, Van Vuren (2005) found that the variability in the design water levels due to bed level changes can be significant compared to centimetre-accuracy of the hydraulic loads defined in the safety assessment process in the Netherlands.

3.3.2. Bed level as a deterministic variable

The river bed level is treated as a deterministic variable in the current Dutch flood safety framework. For the safety standards derivation, the bed level configuration for the 2050 situation was defined the same as the configuration in 2015 (Van Velzen, 2011). For the safety assessment instruments, the bed level schematization followed analysis as to which schematization to use in the hydraulic loads calculation (De Waal et al., 2014). Some potential options included choosing the most recent bed level measurement, an average over several years, a schematization at the start or end of the assessment period. For the 2017-2023 assessment round, it was decided to adopt the most recent measurements, as of 31 March 2014, for the bed level schematization in the hydrodynamic model (De Waal et al., 2014). Some advantages to this assumption are that it is simple, allows for reproducible analysis and avoids room for discussion in its methodology. The assumption on the bed level schematization for the 2023 - 2035 assessment round has not been officially published yet (see Section 2.1.3).

The previous morphological consideration regarding the definition of the bed level configuration was considered conservative, given the ongoing erosion trend in the upper river sections in the Netherlands, which would reduce the hydraulic loads with time. However, this assumption is not conservative in the lower sections of the Dutch Rhine, where the river bed shows aggradation trends (Van Denderen, 2022; Van Vuren, 2005) that can be enhanced by sea level rise (Ylla Arbós et al, 2023; Blom, 2016). Therefore, the fixed-bed assumption in the current framework could lead to an underestimation of the future hydraulic loads in these lower river sections.

3.3.3. Morphological considerations in the model uncertainty

Section 2.1.3 describes and quantifies the uncertain morphological phenomena considered in the model uncertainty of the water levels calculated in the WBI. The focus of the model uncertainty lies on bedform evolution during extreme discharges; however, there still remains great uncertainty in this phenomenon. Other sources of uncertainty such as large-scale bed level changes and their impact on bifurcation morphodynamics and the hydraulic loads are not addressed in the model uncertainty.

The uncertainty in the bed level configuration can be incorporated into the model uncertainty, despite treating it as a deterministic variable. The bed level long-term aggradation trend in the lower river sections can be added as a positive mean deviation, or bias, whereas the shorter-term bed level variability due to migrating sediment waves can be incorporated into the standard deviation of the model uncertainty. This modification of the model uncertainty is relevant at the lower river sections; however, it is less significant in the upper river sections where the current fixed-bed assumption yields conservative, or safe, hydraulic loads. A quantification of the impacts on the hydraulic loads due to both the bed level trend and the bed level variability is required to define the river hinge point location at which the hydraulic loads increase due to large-scale bed level changes.

3.4. Incorporating large-scale bed level changes into flood safety in the Netherlands

Flood safety in the Netherlands can be divided into two time scales: a) long-term analysis for the derivation of the safety standards and b) short-term analysis for the safety assessment every 12 years. Both elements have fundamentally different characteristics and purposes. The relevance of river morphodynamic uncertainties, and the methods in which they are assessed, also vary between these two time scales. Therefore, morphodynamic approaches to be incorporated into the long-term and short-term flood safety in the Netherlands are independently analyzed and proposed in this thesis.

3.4.1. Framework for long-term flood safety

For the safety standards derivation, I propose to incorporate future large-scale bed level changes via morphodynamic modelling scenarios (Figure 3.2). Morphodynamic modelling approaches are more appropriate than observation based methods to quantify the long-term uncertainties associated to the safety standards derivation process. I propose to incorporate the uncertainty in future river discharge, future sea level rise, future river maintenance and future bifurcation morphodynamics. These complex long-term uncertainties are relevant for the morphological evolution of the Dutch Rhine (see Section 2.2.4). Given that they are epistemological uncertainties, I propose to analyze them via deterministic scenarios. For example, morphodynamic models should include scenarios for a) different sea level rise rates, b) maintained, reduced or intensified river dredging and c) ongoing unstable behaviour at the Pannerden bifurcation or its maintenance or re-stabilization via interventions.

The proposed flood risk assessment framework includes a decision-making step to define the hydraulic loads based on all the final bed level configurations calculated via the morphodynamic modelling scenarios. I recommend to incorporate this step after calculation of the hydraulic loads and failure probabilities for each final bed level configuration. An ensemble of the hydraulic loads from different bed level configurations may yield a conservative set of hydraulic loads, as some morphological scenarios can lead to higher hydraulic loads in some river sections, but lower hydraulic loads in others river sections. Furthermore, it is recommended to compare the variability in the failure probability due to the different morphological scenarios against the safety standards classes, which are defined with increments of factor 3 (see Section 2.1.2). This provides insights of the relevance of the long-term bed level variability compared to other uncertain sources within the flood risk assessment.

The proposed framework assumes some simplifications regarding the impacts and uncertainties of future bed level changes in relation to flood risk. First, the influence of large-scale bed level changes on the strength of the flood defences is not addressed. As this relationship is dependent on local geotechnical conditions of the flood defences' foundation, it is not feasible to analyze them at a large-scale, but rather on a case by case basis. Therefore, the framework incorporates the effect of large-scale bed level changes into the hydraulic loads only. Second, additional uncertainty sources in river morphodynamics are not included within the framework. These uncertainty sources include the short-term discharge variability, the parameters of the sediment transport formulas, the hydraulic roughness, among others, which are assumed to have a smaller effect on the long-term morphodynamic response compared to the uncertainties discussed in the proposed framework. However, it is recommended to investigate their relative importance and evaluate their incorporation into the framework via stochastic methods.

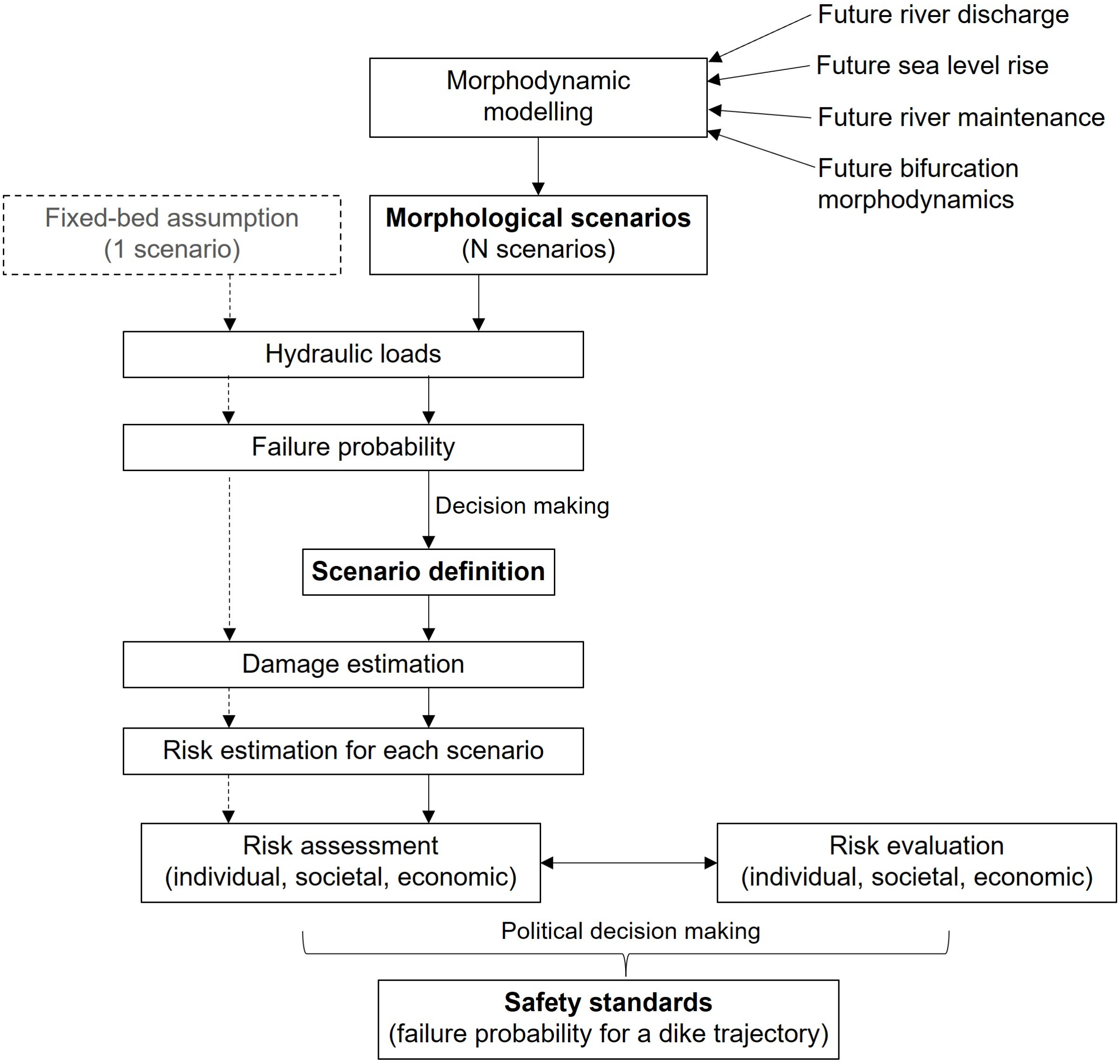


Figure 3.2: Incorporating large-scale bed level changes into the long-term flood safety framework in the Netherlands. The current morphological consideration is shown in dashed boxes

3.4.2. Framework for short-term flood safety

For the safety assessment process, I propose to incorporate large-scale bed level changes via the analysis of past river bed measurements (Figure 3.3). Considering the short-term assessment period of 12 years, it is possible to make inferences in the near future bed level behaviour based on the recent past. I propose to analyze the most recent 15 year bed level measurements, which includes 3 additional years as the hydraulic loads are defined approximately 3 years ahead of the start of the cycle. This approach is feasible given the availability of regular bed level measurements in the Dutch Rhine. Furthermore, this observation based approach matches the cost-effectiveness characteristic of the WBI, where morphodynamic modelling approaches may be too complex to be incorporated.

The analysis of bed level measurements in the proposed framework focuses on large-scale features, averaged over lengths of 300 m or more. Therefore, the variability on the bed geometrical schematization due to small bedforms is assumed not to significantly affect the hydraulic loads. However, they may influence the flow resistance and hydraulic loads during extreme conditions (see Section 2.2.2). The proposed framework focuses only on the large-scale bed level changes impact on the hydraulic loads, which can be superimposed to the effect of bedforms on the flow resistance.

Both the trend in bed level changes and the variability around it are present in the bed level measurements. Large-scale sedimentation and erosion waves can be observed in past measurements; however, shorter-term variability due to migrating sediment waves are also entangled in them (see Section 2.2.1). It is recommended to analyze both the trend and variability by defining different spatial and time scales. For example, yearly bed level measurements can capture the evolution of large-scale sediment waves, but only snapshots of shorter sediment waves. Monthly bed level measurements can capture the variability in the bed level due to these shorter migrating sediment waves.

Given the erosion trend in the upper river sections, the most recent measurement represents a conservative assumption for the hydraulic loads calculation during the next 15 years. However, the lower river sections show a sedimentation trend, which is not addressed in this assumption. Therefore, it is proposed to maintain the bed level schematization as the last available measurement, but update the hydraulic loads in the lower river sections via the model uncertainty (see Section 3.3.3). The trend and variability of the hydraulic loads associated to large-scale bed level changes are incorporated into the mean and standard deviation of the model uncertainty, respectively, if negative implications on the hydraulic loads are found. This approach allows to maintain the simplifying fixed-bed assumption while incorporating the impacts of large-scale bed level variability into the hydraulic loads.

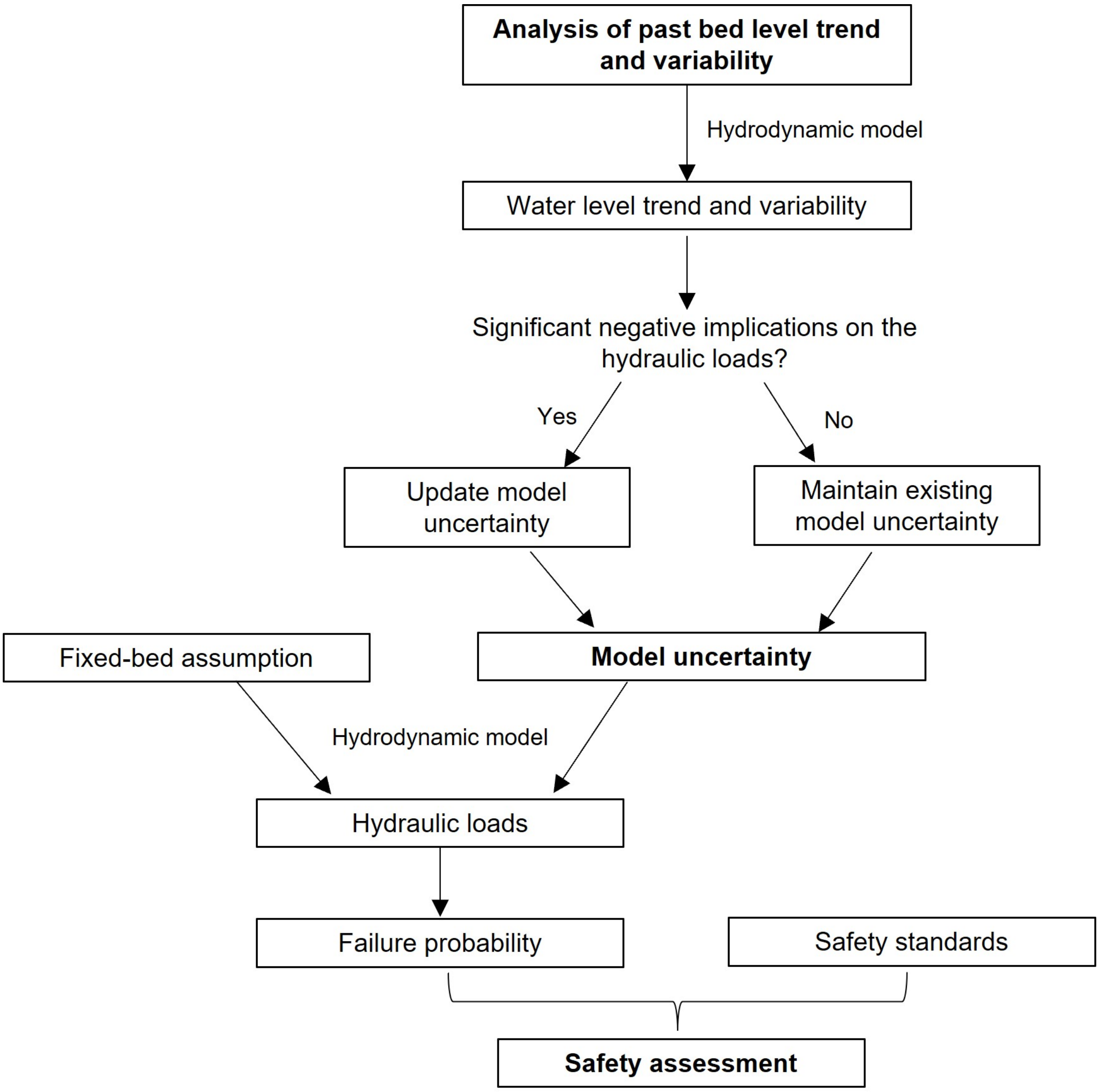


Figure 3.3: Incorporating large-scale bed level changes into the short-term flood safety framework in the Netherlands

4

Application to long-term flood safety in the Dutch Rhine

4.1. Introduction

In this chapter, the proposed framework in Section 3.4.1 is applied to the long-term situation of the Dutch Rhine. In order to do so, results from an existing morphodynamic model are adopted (Ylla Arbós et al., 2023). Based on this model, the impacts of large-scale bed level changes in the year 2050 and 2100 are quantified in terms of hydraulic loads and failure probabilities. These are compared against the results obtained following the fixed-bed assumption in the current flood safety framework in the Netherlands. Deviations to the proposed framework may arise depending on the assumptions of the adopted morphodynamic study.

Section 4.2 and Section 4.3 present the methods applied and the results obtained, respectively. The analysis is divided into three main components: a) analysis of the existing morphodynamic model assumptions and results, b) calculation of hydraulic loads considering large-scale bed level changes, and c) calculation of the failure probability considering large-scale bed level changes. The main findings of this Chapter are summarized in Section 4.4.

4.2. Methods

4.2.1. Morphological scenarios of the Dutch Rhine in 2050 and 2100

The proposed long-term flood safety framework in Chapter 3 aims at representing possible scenarios for future river discharge, sea level rise, river management and morphological evolution at bifurcations via morphodynamic modelling scenarios. Recently, Ylla Arbós et al. (2023) developed a morphodynamic model of the long-term response of the Rhine up to 2100 under different river discharge and sea level rise scenarios related to climate change scenarios. This model considers single scenarios in future river management and future morphological evolution at bifurcations, but does not account for their uncertainty via additional scenarios. However, it is suitable for the application of the proposed framework under limited morphological scenarios. The main characteristics of the morphodynamic model are outlined below:

- The model is a one-dimensional deterministic morphodynamic model, SOBEK-RE (Deltares, 2012), that calculates bed level changes through mass conservation of bed sediment. The sediment transport formula accounts for a threshold of motion and hiding and exposure effects.
- The Pannerden bifurcation morphological behaviour is modeled with a highly simplified nodal point relation that determines the sediment partitioning among the branches. At this bifurcation, instability is observed where the Waal branch consistently increases its water conveyance capacity at the expense of the Pannerden Canal.
- The model accounts for gravel nourishment on the German part of the Rhine until 2020, and dredging over the lowermost 25 km of the Waal River until 2025.

- The results of the highly schematized model aim at finding large-scale and multi-decadal trends and at providing an order of magnitude of the channel response.

Climate scenarios constitute the main analysis variables in the model developed by Ylla Arbós et al. (2023). For instance, high-end warming and moderate warming climate scenarios were studied to quantify their impact on the long-term river response. These scenarios were related to changes at the river controls that define the channel morphological response, namely the upstream river discharge, upstream sediment flux and the downstream stage-discharge relationship. It was found that effect of the upstream sediment flux scenarios is neglectable in the Dutch part of the Rhine (Ylla Arbós et al., 2023), but the scenarios in the other two river controls have significant impacts on the morphological response.

The future morphological evolution at the bifurcation is modelled considering a single scenario via the calibration of the nodal relationship. Similarly, future river maintenance is modelled via a single scenario considering that no dredging or river interventions take place between 2025 and 2100. These considerations are expected to result in conservative morphological scenarios. This means that the hydraulic loads calculated under these morphological scenarios are expected to fall within the upper spectrum of the hydraulic loads calculated from all possible future scenarios. For instance, no dredging in the lower Waal would lead to an increase in the bed levels that are expected to increase the hydraulic loads compared to a scenario where dredging is maintained until 2100.

For this thesis research, the morphological scenarios were derived based on the results from Ylla Arbós et al. (2023). The scenarios were defined for the years 2050 and 2100, considering that the current flood safety standards were derived for the 2050 situation, and that the current flood safety aims at ensuring the protection level with a long-term vision. Table 4.1 shows the morphological scenarios considered in the analysis for the long-term flood safety in the Dutch Rhine.

Scenario	Description
Reference case	The bed level is fixed in time as the latest measurement in 2015, according to the current framework consideration.
Base model	The bed level is updated according to the morphodynamic model results for the base case.
High-end warming	The bed level is updated according to the morphodynamic model results for the high-end warming climate scenario.
Moderate warming	The bed level is updated according to the morphodynamic model results for the moderate warming climate scenario.

Table 4.1: Morphological scenarios for the long-term flood safety analysis in the Dutch Rhine. The base model, high-end warming and moderate warming scenarios are based on the results from Ylla Arbós et al. (2023)

4.2.2. Hydraulic loads considering bed level changes

Following the proposed approach in Chapter 3, the impact of large-scale bed level changes on the hydraulic loads is estimated for the long-term morphological scenarios. This research focuses on the water levels and neglects the wave action as large-scale bed level changes are not expected to influence the wave characteristics. The first objective of this analysis is to quantify the impact on the water levels of each morphological scenario relative to the fixed-bed assumption (reference case), which is expressed by the difference in the computed water levels. The second objective is to provide the basis for the calculation of failure probabilities, which requires the assessment of several extreme discharge events with different exceedance probabilities. Therefore, several simulations are required per morphological scenario in order to preserve the statistical properties of the upstream discharge into the water levels at the flood defences.

Hydrodynamic model selection

A hydrodynamic model is required in order to calculate the water levels at the flood defences. The analysis aims at providing first order estimates of the impact of bed level changes into flood safety. Thus, simplified and computationally cheap models are preferred, which also allow for more efficient simulation and analysis of several scenarios. This is consistent with the nature of the morphological input, which were derived from a highly simplified one-dimensional morphodynamic model.

It is decided to use a one-dimensional hydrodynamic model, SOBEK 3.7.25.55022 (Deltares, 2023), for this research. An existing one-dimensional model (Maas et al., 2023) of the Dutch Rhine branches served as starting point given its representativeness and simplicity. This model was developed based on the 2D river schematizations and calibrated against the 2D hydrodynamic model used in the formal derivation of the hydraulic loads within the current flood safety framework. Therefore, it is representative of the Dutch Rhine river morphology, while allowing faster simulation times via a simple one-dimensional model.

The existing model (Maas et al., 2023) was simplified to focus only on the Waal branch of the Rhine (Figure 4.1). The river geometry is represented by cross-sections, composed of main channel and floodplains, spaced approximately every 500 meters. The upstream boundary condition is defined as a discharge time series at Dornick, approximately 14 km upstream of Lobith, and the downstream boundary condition is defined as a water elevation-discharge relationship at Hardinxveld. The model computes the flow conditions by solving the De Saint Vernant equations for unsteady one-dimensional flow.

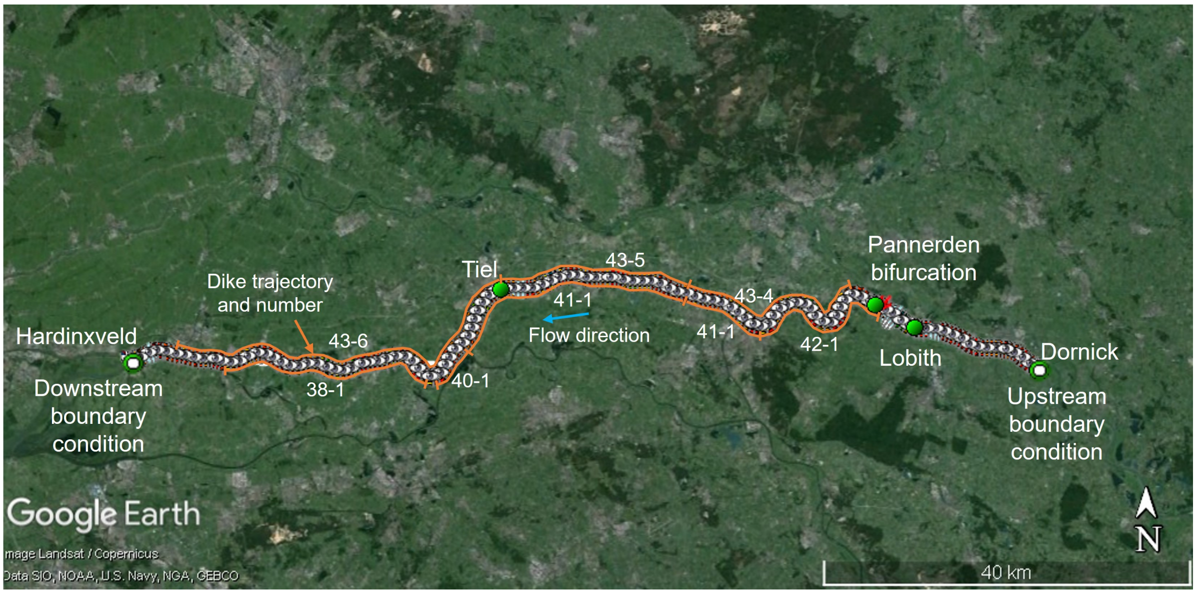


Figure 4.1: Hydrodynamic model of the Dutch Rhine. Model adapted from Maas et al. (2023). Map source: Google Earth

Upstream boundary condition

The upstream boundary condition is based on the discharge statistics derived from GRADE (Generator for Rainfall and Discharge Extremes), which are applied in the current flood safety framework (Chbab et al., 2017b). A Generalized Extreme Value probabilistic distribution is fitted to the results from GRADE in order to simplify the probabilistic representation of the upstream discharge. More details on the selection of probability distribution parameters are provided in Appendix A. As we are interested only in the maximum water level during a flood event, steady-state peak discharges are simulated as the upstream boundary condition.

The probability density function (PDF) of the water levels at the flood defences is calculated, as it is required for the calculation of the failure probability, see Section 4.2.3. This PDF is obtained based on the statistical properties of the upstream discharge, which are transformed into water levels via the hydrodynamic model (Figure 4.2). A total of 15 peak discharges, ranging from 2000 m^3/s to 17000 m^3/s, are simulated for each morphological scenario in order to conserve the shape of the probability distribution (see Apendix A). This allows to approximate the statistical properties of the discharge and water levels, without requiring thousands of simulations typically necessary to capture these properties via probabilistic sampling techniques.

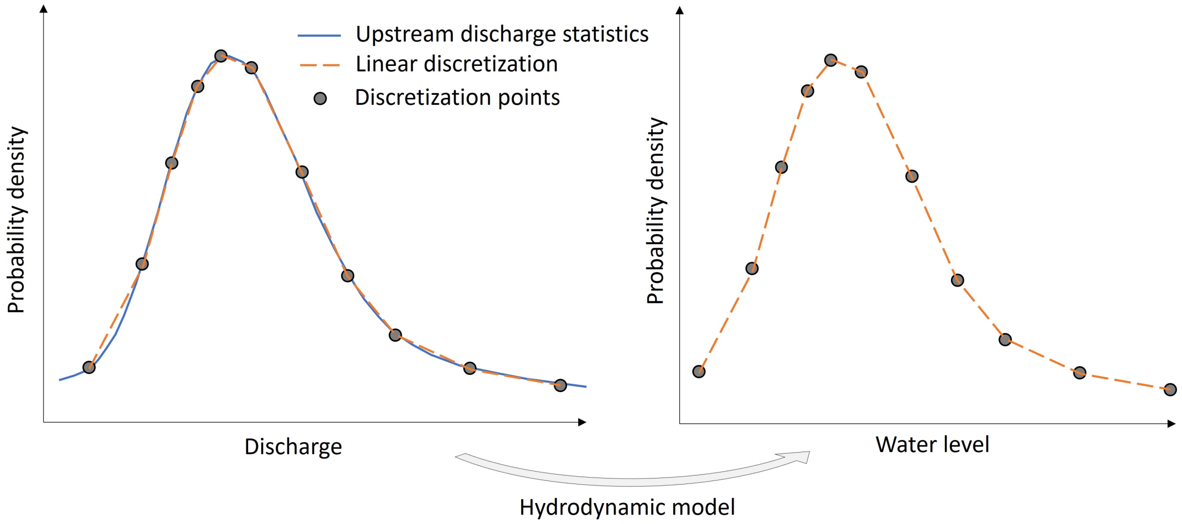


Figure 4.2: Schematized method for calculating the probability density function of the water levels

Downstream boundary condition

The downstream boundary condition is defined as a stage-discharge relation (Maas et al., 2023). This relation changes according to the rate of sea level rise in each climate scenario. However, since the focus of the hydrodynamic analysis is on relative water level differences due to bed level changes alone, the influence of sea level rise cancels out. In other words, two morphological scenarios under the same climate scenario show the same water level difference as they are imposed the same sea level rise rate at the downstream end. For consistency within the hydrodynamic model, the stage-discharge relations in the year 2050 and 2100 are updated based on the sea level rise trend corresponding to the centerline of the KNMI (2015) projections.

The downstream stage-discharge relation may also change due to erosion or sedimentation of the riverbed at the lower end of the river model (Hiemstra et al., 2022; Van Vuren, 2005). This change depends not only on the bed level response within the model domain, but also on the morphological response in the downstream estuarine area. Since no estimations of the long-term morphological changes at the estuarine area are available, it is uncertain how the stage-discharge relation at the boundary may be affected. Based on a sensitivity analysis, shown in Appendix A, this effect is found to be negligible in the river domain of interest.

Water discharge partitioning at bifurcation

The water discharge partitioning at the Pannerden bifurcation is determined by a constant distribution ratio in order to avoid second-order effects on the partitioning caused by the bed level changes along the Waal. In reality, the discharge partitioning may be influenced by the morphological changes at the two bifurcates: Waal and Pannerden Canal. This river system analysis falls out of the scope of this research, and a simplifying assumption was made in order to isolate the effect of the bed level changes in the Waal branch only. The partitioning ratios were assumed as 2/3 and 1/3 into the Waal and Pannerden Canal, respectively, which approximate typical observed discharge ratios under high flow conditions in the Dutch Rhine (Chowdhury et al., 2023).

The upper Waal shows enhanced incision due to instability in the Pannerden bifurcation according to the morphodynamic modelling results (Ylla Arbós et al., 2023). This means that the discharge intake into the Waal increases with time. Each bed level configuration in the year 2050 and 2100 will have potentially a different discharge partitioning ratio at the bifurcation. However, this is not accounted for in the hydrodynamic model as further research around the bifurcation morphodynamics at a more detailed scale is required. Therefore, the assumed discharge partitioning ratios of 2/3 and 1/3 are expected to result in lower water levels in the Waal than expected due to the enhanced incision trend in the upper Waal.

Incorporating bed level changes into hydrodynamic model

The river schematization in the existing model is defined by cross-sections representative of the year 2020 (Maas et al., 2023). The existing model is based on a two-dimensional schematization that captures the existing river morphology; therefore, the existing cross-sections are maintained generally undisturbed. The adjustments due to long-term bed level changes are incorporated only to the river main channel (Figure 4.3), which is considered the morphological active area in the morphodynamic model adopted (Ylla Arbós et al., 2023). The morphological changes in the floodplains are neglected.

The cross-sections for the reference case scenario were updated based on observed bed level changes between 2015 and 2020. The relative change in the bed levels between these 5 years was applied to the existing model to infer the 2015 geometry while maintaining the overall schematization in the existing model. A dataset analyzing the observed bed level in the Dutch Rhine from 2000 to 2020 was used for this purpose. Chapter 5 describes in more detail this dataset, as it is mainly applied to the short-term flood safety analysis.

The cross-sections for the morphological scenarios were updated based on the relative bed level change derived from the morphodynamic model (Ylla Arbós et al., 2023). These were expressed as the relative difference in the years 2050 and 2100 compared to the 2000 situation. Therefore, a first update of the existing model to the year 2000 was performed, followed by the addition of the relative bed level changes to the years 2050 and 2100.

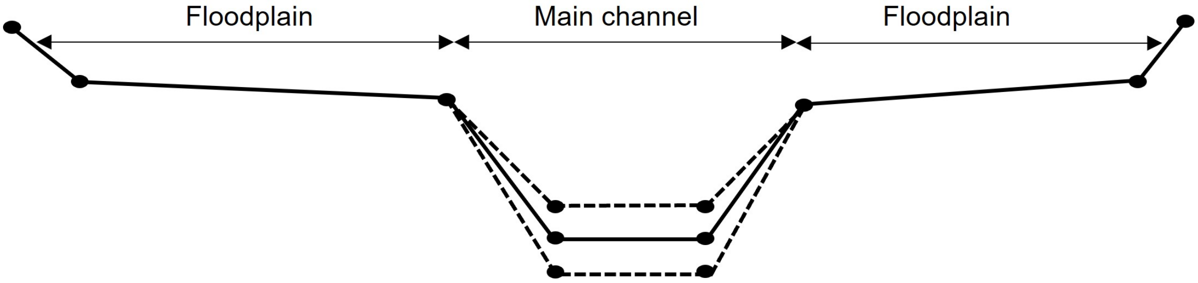


Figure 4.3: Schematic updating of the cross sections within the hydrodynamic model. Full line represents the original cross section. Dashed lines represent final cross section after bed level changes applied in the main channel.

4.2.3. Failure probability considering bed level changes

According to the proposed approach in Chapter 3, the impact of large-scale bed level changes on the failure probability is determined from the changes on the hydraulic loads. Additionally, information on the strength of the flood defences is required in order to calculate the failure probability. The strength of the flood defences is represented in a simplified manner, considering that the overall objective is to provide an order of magnitude of the impact of bed level changes on flood safety. This is consistent with the hydraulic loads estimation methods and with the nature of the morphodynamic model adopted.

The dike strength can be represented by fragility curves in a simple manner. They represent the conditional failure probability of a dike section for a given failure mechanism and a given load. By integrating the product of the fragility curve and the PDF of the load, the failure probability P_f of a dike section for a given failure mechanism can be computed (Jonkman et al., 2021), see Equation 4.1. The estimation of the PDF of the water levels is described in Section 4.2.2 and Figure 4.2.

$$P_f = \int_0^\infty f_H(h).F_R(h)\, dh \tag{4.1}$$

In which:

- $f_H(h)$ is the probability density function of the water hydraulic load;
- $F_R(h)$ is the cumulative distribution of resistance given a certain hydraulic load level, or fragility curve.

The formal safety assessment process stated in the WBI consists of the application of probabilistic models in order to compute the failure probability of a dike section and dike trajectory. In this research, a simplified representation via fragility curves is adopted in order to reduce the number of control variables and allow for a more insightful analysis of the physical processes associated to the incorporation of morphological scenarios.

The main failure mechanisms in the area of study are piping, macro stability, and overtopping, for which current dike reinforcements are being carried out via the Flood Protection Programme (HWBP, 2022). Fragility curves for piping and macro stability have been developed by Rijkswaterstaat and HKV (Kolen et al., 2021) for the location specific conditions in the Netherlands. For overtopping, fragility curves have not been developed given that they depend mainly on the dike crest height and other methods are used to calculate its failure probability within the WBI. In this research, the fragility curves developed by Kolen et al. (2021) are adopted as they capture updated site-specific conditions at similar spatial scale as in the hydrodynamic model, every 500 m to 1 km. Other failure mechanisms are not addressed as their derivation at this scale falls out of the scope of this research. However, this methodology can later be extended to all relevant failure mechanisms by applying the formal assessment process stated in the WBI.

The fragility curves for piping were defined by Kolen et al. (2021) based on the Sellmeijer equation, which depends on the aquitard and aquifer thicknesses, the soil permeability and other geotechnical characteristics at location-specific conditions. For macro stability, the strength is defined by the drained and undrained strength of the soil materials, the dike geometry, the presence of an inner berm, among other characteristics. The fragility curves are assumed independent of the morphological scenario; in other words, large-scale bed level changes do not influence the dike strength. The possible influence of bed level changes requires a more detailed analysis, where the specific foundation configuration and geotechnical properties are linked to the bed level changes. For this study, the possible interrelation between bed level changes and dike strength is neglected.

The main load for the failure mechanisms piping and macro stability is the water level, which is influenced by the bed level changes in the morphological scenarios. The PDF of the water levels is updated for each scenario by maintaining the statistical properties of the upstream discharge, represented by 15 discharge conditions. The PDF may shift towards higher or lower water levels depending on the sedimentation and erosion of the river bed, leading to higher or lower failure probabilities, respectively.

4.3. Results

4.3.1. Morphological scenarios of the Dutch Rhine in 2050 and 2100

First, the river bed predicted for the years 2050 and 2100 by the morphodynamic models are compared against the fixed-bed assumption in the current safety standards derivation, referred as reference case (Figure 4.4). The predicted configuration in the morphological scenarios show lower bed levels in the upper section of the Waal, between km 870 and 915, compared to the reference case. These lower bed levels, up to 2 m, are expected to result in a reduction in the hydraulic loads, thus reducing flood risk. However, lower bed levels can also result in weakening of the foundation at the flood defences, which increases flood risk (Section 2.2.2). This interrelation between bed level changes and the dike strength is not quantified in this case study application (see Section 4.2.3). The bed is more or less stable at the fixed layers around km 875, 885 and 925.

In the lower section of the Waal, between km 930 and 950, higher bed levels are predicted for the 2050 and 2100 base models, in the order of 0.50 m and 0.80 m, respectively. The high-end and moderate warming scenarios do not significantly influence the bed response by the year 2050, since the river response is mainly driven by past human intervention (Ylla Arbós et al, 2023). However, the climate scenarios have more influence by the year 2100. Under the high-end warming scenario, the predicted bed level is on average 1.20 m higher than in the reference case in the lower section of the Waal.

The fixed-bed assumption in the current safety standards is a conservative consideration for the calculation of the hydraulic loads at the upper section of the Waal, where the bed level decreases in time. However, this does not hold for the lower river section, where higher bed elevations could lead to higher hydraulic loads in the future. Potentially, the dike trajectories 38-1 and 43-6 could be subjected to higher hydraulic loads in the year 2050 than predicted following the current fixed-bed assumption.

Relatively large bed steps are modelled at the Pannerden bifurcation, in the order of 3 m and 4 m in the years 2050 and 2100, respectively. They are not expected to create damming effects, since they are considerably smaller than the flow depths under high discharge conditions. Furthermore, any possible local misrepresentation of the bed steps dimensions would not influence the Waal since the flow information travels in the upstream direction.

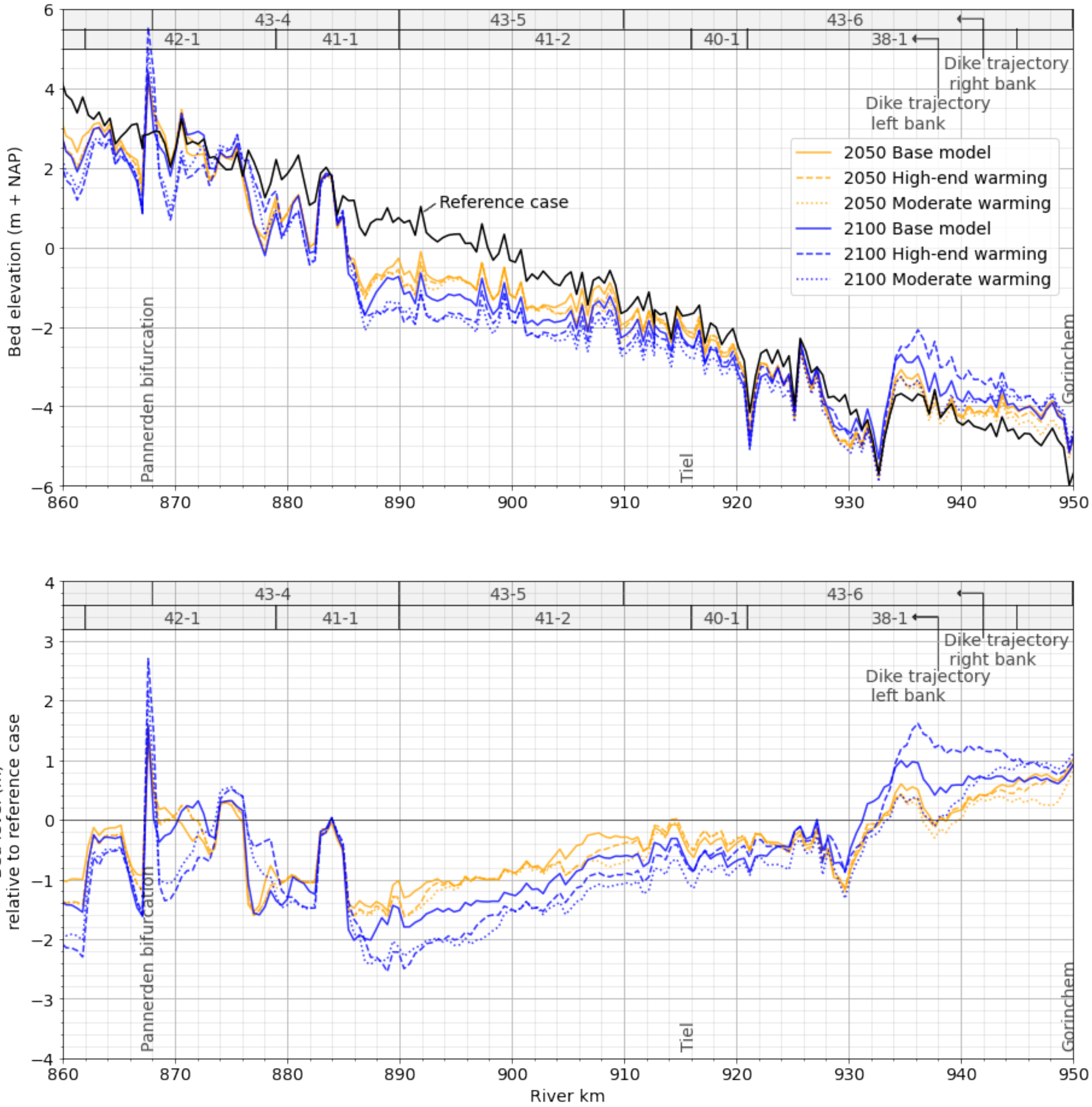


Figure 4.4: Top: bed level under different morphological scenarios. Reference case represents the bed level used in the current safety standards derivation. Bottom: bed level relative to the reference case under different morphological scenarios based on the morphodynamic modelling results from Ylla Arbós et al. (2023)

4.3.2. Hydraulic loads considering bed level changes

The impact on the hydraulic loads is first addressed for high discharge conditions, which are expected to be the main contributors to the failure probability. The water level increment relative to the reference case is shown in Figure 4.5 for a peak discharge equal to 15000 m^3/s at Dornick. The water level increment for other high discharges, above 9000 m^3/s, show a similar behaviour.

Overall, the modelled bed tilting trend translates into lower water levels in the upper Waal and into higher water levels in the lower Waal. This effect is enhanced in the year 2100. The climate scenarios show small variability in the year 2050, but significant variability in the year 2100, which agrees with the bed level behaviour in Figure 4.4. The water levels in the upper Waal are lower under the climate scenarios, which is consistent with the enhanced incision trend due to the more severe high flow conditions (Ylla Arbós et al, 2023). As expected, this means that the current fixed-bed assumption is a conservative assumption for the estimation of hydraulic loads in the upper Waal, which are on average 0.15 m and 0.30 m higher compared to the morphological scenarios in 2050 and 2100, respectively. However, the future discharge partitioning at the Pannerden bifurcation into the Waal could increase with time due to the enhanced incision (See Section 4.2.2). This could lead to higher water levels, under which the fixed-bed assumption is no longer conservative in the upper Waal.

Downstream of km 910, the water levels are higher when considering morphological scenarios. In the year 2050, the base model represents the most severe scenario with increments in the water level in the order of 0.20 m in the lower end. The high-end and moderate warming scenarios show similar or slightly smaller water level increments. In the year 2100, the water level increases by 0.25 m under the base model scenario. The high-end warming represents the most severe scenario with increments in the water level in the order of 0.40 m. As discussed for the upper Waal, the water levels can be higher when considering an increased discharge partitioning ratio at the Pannerden bifurcation into the Waal.

Considering that the incision of the high-end and moderate warming scenarios in the year 2100 are similar (Figure 4.4), it would be expected that the water levels be also similar. However, the moderate warming scenarios consistently resulted in lower water levels in the middle section of the Waal (km 880 - 910). This can be explained by the upstream influence of the increased water levels in the lower Waal. Since the high-end warming scenario yields significantly higher water levels in the lower Waal, this increment extends upstream via a backwater curve, increasing the water levels in the middle Waal. In other words, the increment in the water levels affects a longer river section than the section that presents bed sedimentation. As a result, also the dike trajectory 40-1 shows higher water levels when considering morphological scenarios as compared to the reference case.

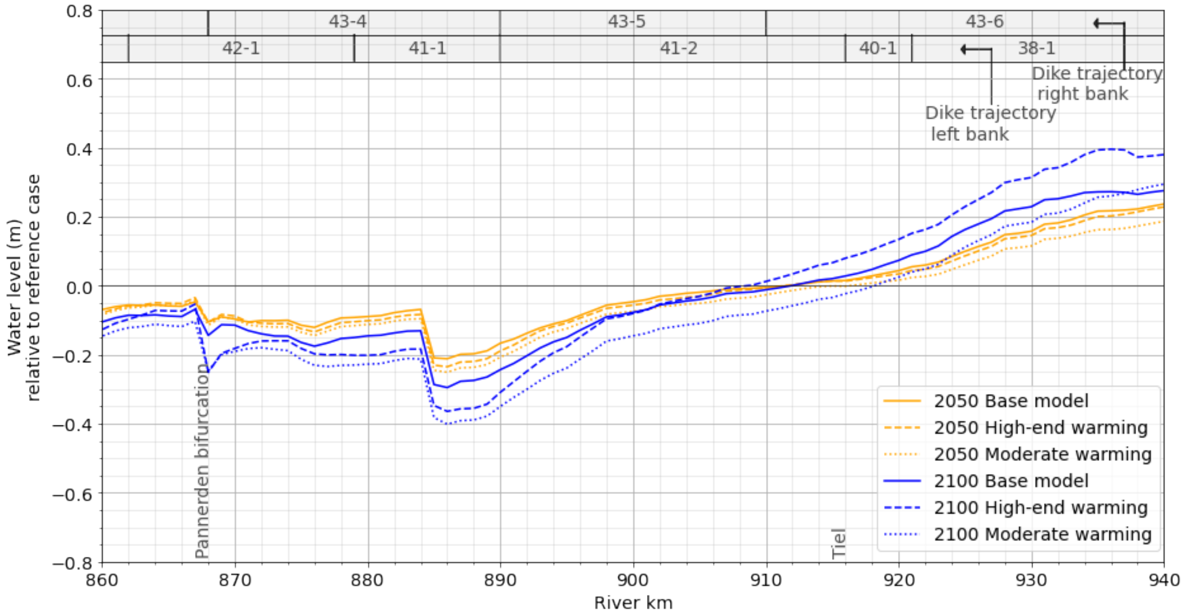


Figure 4.5: Water level increase relative to the reference case under different morphological scenarios for peak discharge at Dornick of 15000 m^3/s. Morphological scenarios are based on the morphodynamic modelling results from Ylla Arbós et al. (2023)

The water level increment was averaged over the kilometers 920 - 940 for all discharge conditions and morphological scenarios (Table 4.2). At low discharge values, 2000 to 4000 m^3/s, the effect of bed level changes in the morphological scenarios is stronger, since the flow is mainly driven by the main channel geometry. As the discharge increases, the water level variation reduces as the flow approaches the floodplains. At 7000 m^3/s, the water level increment is the smallest in all scenarios due to its attenuation at the main channel-floodplain transition.

For discharges equal to 9000 m^3/s and higher, the water level increments show a consistent behaviour. In this discharge domain, the water level is less affected by the bed level variation in the main channel, since the floodplains convey the greater flow fraction. The averaged water level in the year 2050 is 0.10 to 0.15 m higher than in the reference case, depending on the morphological scenario. In the year 2100, the averaged water level is 0.17 to 0.30 m higher depending on the morphological scenario.

Year	2050			2100		
Discharge (m^3/s)	Base model	High-end warming	Moderate warming	Base model	High-end warming	Moderate warming
2000	0.10	0.08	0.03	0.19	0.37	0.11
4000	0.19	0.17	0.09	0.31	0.51	0.21
5000	0.17	0.15	0.08	0.28	0.46	0.18
5600	0.15	0.13	0.07	0.23	0.35	0.15
6200	0.08	0.07	0.03	0.15	0.24	0.09
7000	0.05	0.04	0.02	0.11	0.17	0.04
9000	0.14	0.13	0.09	0.21	0.31	0.16
10000	0.15	0.13	0.10	0.22	0.31	0.17
11000	0.15	0.14	0.10	0.21	0.31	0.17
12000	0.15	0.14	0.10	0.21	0.30	0.17
13000	0.14	0.13	0.10	0.20	0.28	0.16
14000	0.15	0.13	0.10	0.20	0.29	0.17
15000	0.15	0.14	0.11	0.21	0.30	0.18
16000	0.16	0.15	0.12	0.22	0.31	0.19
17000	0.17	0.16	0.12	0.22	0.31	0.19

Table 4.2: Water level increase (in m) of morphological scenarios relative to reference case, averaged over km 920 - 940. Morphological scenarios are based on the morphodynamic modelling results from Ylla Arbós et al. (2023)

4.3.3. Failure probability considering bed level changes

The impact of the water level increment on the failure probability is quantified by integrating the product of the water level probability density and dike fragility curves (See Section 4.2.3). The interaction between these components is illustrated in Figure 4.6 for a dike section at the river km 930, where morphological scenarios led to higher water levels. The impact of the increment in the water level is shown for the 2100 base model scenario in dashed lines.

The failure probability due to the piping is attributed to flow conditions with water discharges between 7000 and 15000 m^3/s (Figure 4.6, right plot). On the other hand, lower water discharges also contribute to the failure probability due to macro stability. In both cases, the influence of the water level increments is significant only for water discharges greater than 7000 m^3/s. This can be explained by the fragility curves, which show considerably lower failure probabilities for low water levels. Furthermore, as the discharge approaches 7000 m^3/s, the water level increments in the morphological scenarios decrease due to the main channel-floodplain transition, leading to a reduced impact on the failure probability.

The failure probability at a dike section is given by the area under the right plots in Figure 4.6. It is calculated that the failure probability due to piping (in the order of 3x10^{-2}) is higher than the failure probability due to macro stability (in the order of 10^{-2}). Moreover, the morphological scenarios, in dashed lines, have a higher impact on the piping failure mechanism. This occurs as the failure probability due to piping is more susceptible to increments in the water levels than due to macro stability. This is shown by the fragility curve for piping being located mostly at the left side of the one for macro stability.

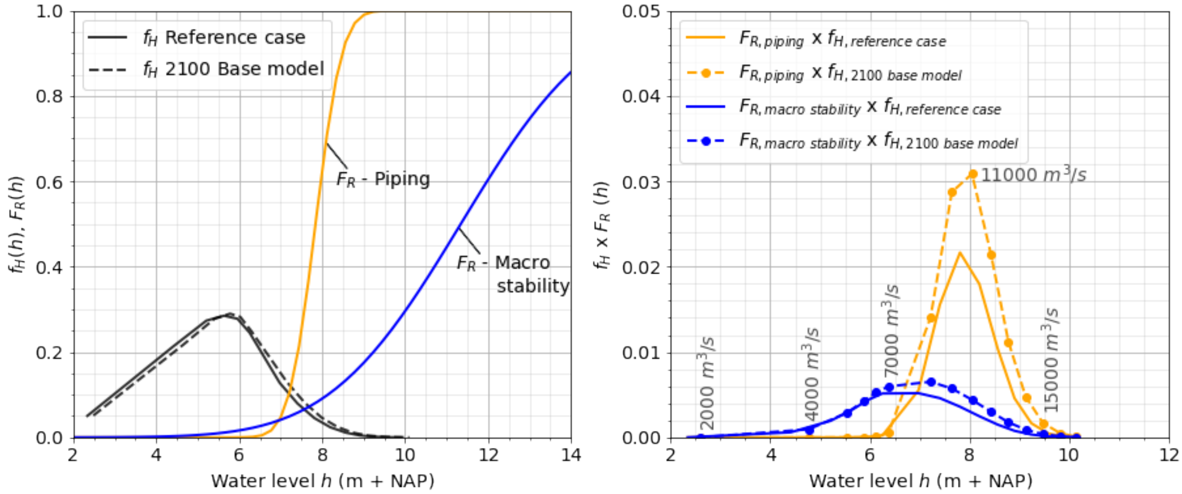


Figure 4.6: Impact of large-scale bed level changes on the failure probability at the dike section level. Left: probability density function of the water level and fragility curves. Right: product of the probability density function and fragility curves. The water levels correspond to km 930. Fragility curves correspond to km 930, right bank. The scenario 2100 base model is based on the morphodynamic modelling results from Ylla Arbós et al. (2023)

The amplification factor of the failure probability with respect to the reference case is shown in Figure 4.7 as a function of space for the dikes along the right bank. In the year 2050, the river sections upstream of km 915 show a reduction in the failure probability due to piping and macro stability by an average factor of 0.3 and 0.2, respectively, relative to the reference case. Downstream of km 915, the failure probability due to piping is amplified up to 1.5 to 1.8 times when considering morphological scenarios; for the macro stability failure mechanism, up to 1.2 to 1.3 times. The base model morphological scenario presents the highest amplification factors of the failure probabilities at km 920 - 940 in the year 2050. The climate scenarios add little variability and result in slightly smaller failure probabilities than in the base model.

In the year 2100, the amplification factors considerably increase and show greater variability among the climate scenarios in the lower river section. In the downstream end, the failure probability due to piping is increased up to 2.0 to 2.5 times; for macro stability, up to 1.3 to 1.5 times. In both cases, the highest amplification is observed in the high-end warming scenario, in agreement with the result obtained for the water level increments. In the upper river sections, the failure probabilities are smaller compared to the reference case, and are reduced on average by a factor 0.5 and 0.3 for piping and macro stability, respectively.

Even though the water levels at km 910 for the 2100 base model (Figure 4.5) show a positive increment, the failure probability amplification factor (Figure 4.7) is below 1 at the same location. This can be explained by analyzing the contribution of all water discharge conditions on the failure probability. Under lower discharge conditions than shown in Figure 4.5, the water level increment is negative. Therefore, the reducing contribution at lower-intermediate discharges is greater than the amplification contribution at higher discharges. The impact of morphological scenarios on the failure probability depends on this interaction between loads and resistance, where the contribution at different discharge levels plays an important role.

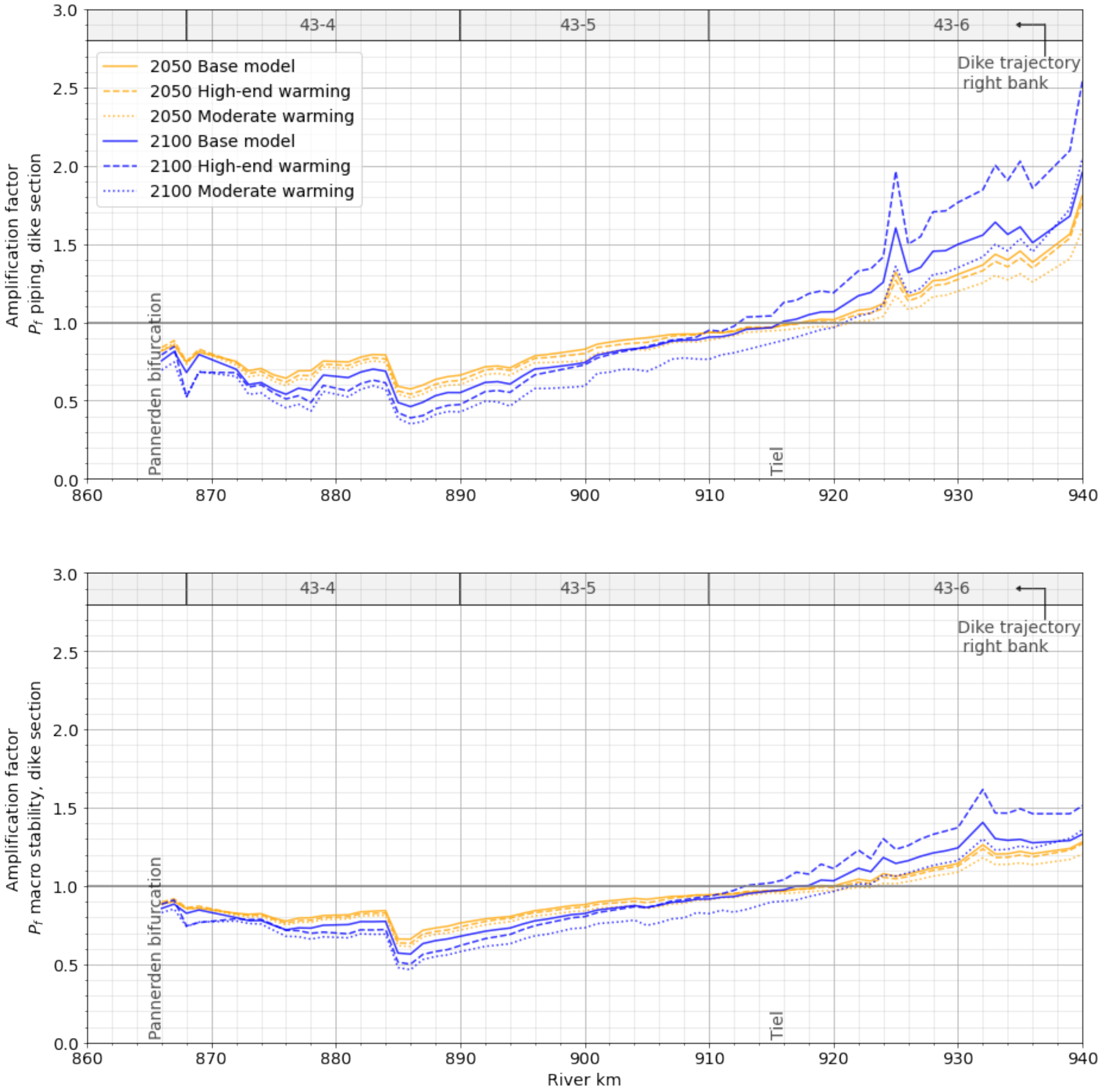


Figure 4.7: Amplification factor, relative to the reference case, of the failure probability at the dike section level under different morphological scenarios. Top: piping failure mechanism. Bottom: macro stability failure mechanism. Failure probabilities correspond to dike sections along the right bank. Morphological scenarios are based on the morphodynamic modelling results from Ylla Arbós et al. (2023)

The amplification factor was then averaged over the km 920 - 940 (Table 4.3), as negative implications on flood risk due to bed level changes concentrate on this section. In the year 2050, the averaged amplification factor is 1.3 for piping and 1.2 for macro stability. The climate scenarios result in slightly smaller amplification factors. In the year 2100, the base model shows an averaged amplification factor of 1.5 for piping and 1.2 for macro stability; under the high-end warming scenario, it increases to 1.9 and 1.4, respectively.

To contextualize the magnitude of the amplification factors in the failure probability, the current standards definitions are revised. The current safety standards are defined as the maximum allowable failure probability of a dike trajectory, consisting of multiple dike sections, for any failure mechanism. They are stated in increments of factor 3, for example: 1/3000, 1/10000, 1/30000 (see Section 2.1.2). Then, the amplification factors shown in Table 4.3 can be considered small in the year 2050, up to 1.3, and significant in the year 2100, up to 1.9. Nonetheless, these results were derived at the dike section level and for specific failure mechanisms via simplified methods. These do not constitute a formal safety assessment, but provide an order of magnitude of the impact of large-scale bed level changes in flood safety.

It should be noted that the amplification effect on the failure probability may also depend on the current strength condition of a dike section. For example, the dike section analyzed in Figure 4.6 shows a smaller resistance against piping than against macro stability. This leads to a higher amplification effect in piping when considering increments in the water levels associated to morphological scenarios. Therefore, the impact of higher water levels could be reduced if a dike is reinforced. Furthermore, the effects of lower bed level changes on the dike strength is not quantified in this case study application (see Section 4.2.3).

Year	2050			2100		
Failure mechanism	Base model	High-end warming	Moderate warming	Base model	High-end warming	Moderate warming
Piping - right bank	1.3	1.3	1.2	1.5	1.8	1.4
Piping - left bank	1.4	1.3	1.2	1.5	1.9	1.4
Macro stability - right bank	1.2	1.1	1.1	1.2	1.4	1.2
Macro stability - left bank	1.2	1.1	1.1	1.2	1.4	1.2

Table 4.3: Amplification factor, of morphological scenarios relative to reference case, of the failure probability at the dike section level averaged over km 920 - 940. Morphological scenarios are based on the morphodynamic modelling results from Ylla Arbós et al. (2023)

4.4. Conclusions

The fixed-bed assumption in the current safety standards derivation was adopted considering a degradation trend in the Waal; however, morphodynamic models predict bed sedimentation in the lower of the Waal in the years 2050 and 2100. Over the lower Waal, the bed level is 0.50 to 0.80 m higher when considering the bed level response at the years 2050 and 2100, respectively, compared to the fixed-bed assumption. Climate scenarios impose more severe conditions in the year 2100, leading to bed levels up to 1.2 m higher under a high-end warming scenario. Further scenarios are recommended to quantify the uncertainty in the morphodynamic modelling assumptions, such as accounting for future river maintenance in the lower Waal.

The water levels under high flow conditions are increased over the lower Waal when considering bed level changes in the years 2050 and 2100, potentially affecting dike trajectories 38-1, 40-1 and 43-6. The fixed-bed assumption could lead to an underestimation of the water levels in the order of 0.10 to 0.15 m in the year 2050 and 0.17 to 0.30 m in the year 2100, based on morphodynamic predictions in the Waal. The failure probability at the dike section due to piping and macro stability are increased on average by a factor of 1.2 to 1.3 over the lower Waal when considering bed level changes in the year 2050. In the year 2100, this effect is amplified to factors up to 1.9 under the high-end warming scenario. Over the upper Waal, the water levels decrease on average by 0.15 m and 0.30 m in 2050 and 2100, respectively, compared to the fixed bed assumption. This is associated to an average reduction in the failure probability at the dike section by 30% and 50% in 2050 and 2100, respectively.

The fixed-bed assumption is presumably conservative for the derivation of hydraulic loads in the upper Waal given the ongoing bed incision trend. However, this incision can also be associated to an increase of the discharge intake into the Waal due to instability at the Pannerden bifurcation. Moreover, bed incision can lead to weakening of the foundation of flood defences. These phenomena associated to the ongoing incision trend in the upper Waal may lead to a higher flood risk than estimated under the fixed-bed assumption. In the lower Waal, the fixed-bed assumption can lead to an underestimation of the water levels and failure probability at the flood defences.

5

Application to short-term flood safety in the Dutch Rhine

5.1. Introduction

In this chapter, the proposed short-term flood safety framework in Section 3.4.2 is applied to the Dutch Rhine. The short-term flood safety is analyzed by evaluating the flood conditions of the Dutch Rhine under different bed level configurations measured in the recent past. The impact of bed level changes is expressed in terms of hydraulic loads and failure probabilities, and are compared against the fixed-bed assumption of the current framework.

Section 5.2 and Section 5.3 present the methods applied and the results obtained, respectively. The analysis is divided into three main components: a) analysis of the past bed level variability, b) calculation of hydraulic loads considering bed level changes, and c) calculation of the failure probability considering bed level changes. The main findings of this Chapter are discussed in Section 5.4.

5.2. Methods

The bed level variability in the Dutch Rhine is analyzed for a period of 15 years. This period considers that the current assessment period in the Netherlands takes place every 12 years and that its technical instruments are derived approximately 3 years ahead. In the Netherlands, the bed level has been measured annually by Rijkswaterstaat since 1926. Until 1999, bed level measurements were performed with single beam echo sounders at cross sections every 25 m. Since 1999, multibeam echo sounders were used to cover the entire length of the river with 1m x 1m resolution measurements (Ylla Arbós et al., 2021).

The bed level variability was evaluated based on an existing dataset of the large-scale bed level features in the Dutch Rhine until 2020 (Ylla Arbós et al., 2021; Chowdhury et al., 2023). In this dataset, the bed level measurements were analyzed to quantify the cross-sectional averaged data along the main river channel. Until 1999, the bed level data was averaged every 1 km along the river axis; from 1999 to 2020, the bed level data was averaged every 100 m. Based on this dataset, the most recent 15 years were selected to assess the bed level variability within the safety assessment process period in the Netherlands.

The water levels were calculated with a one-dimensional hydrodynamic model of the Dutch Rhine. The model specifications are the same as specified in Section 4.2, with the exception of the downstream boundary condition. Sea level rise is not taken into account for the short-term analysis; therefore, the downstream elevation-discharge relationship is equal for the 15 years of analysis. The cross-section data was updated following the procedure specified in Section 4.2 based on the bed level dataset from 2005 to 2020. The failure probability is computed following the procedure in Section 4.2, based on the fragility curves for piping and macro stability defined in (Kolen et al., 2021).

5.3. Results

5.3.1. Bed level variability in the Dutch Rhine during 2005 - 2020

The bed level evolution in the Waal is analyzed from 2005 to 2020 (Figure 5.1). The dataset is composed of yearly bed level measurements, averaged over a distance of 500 m. At this spatial scale, bedforms such as dunes are averaged out, but larger migrating sediment waves are present. The variability due to some of these migrating sediment waves may not be captured at the yearly frequency of the measurements depending on the celerity of the sediment waves (see Section 3.4.2). Therefore, the bed levels shown capture the variability due to slow and long sediment waves, such as the ones due to past channelization, and single snapshots of the variability due to smaller sediment waves, such as the ones due to river interventions at the scales of a few kilometers.

The bed level changes show a large spatial and temporal variability (Figure 5.1). In the upper Waal (river km 867 - 890), the bed shows a general incision trend in time, which reduces in the middle Waal (river km 890 - 920). In the lower Waal (river km 920 - 950), the bed level shows a general sedimentation trend. An aggradation up to 40 cm is observed in the year 2020 around river km 930 compared to the year 2005. At this location, bed aggradation has been associated both to large-scale sediment waves and to intermediate-scale sediment waves caused by the construction of a side channel in 2015 (Van Denderen et al., 2022). Some river sections in the lower Waal show local bed degradation; for instance, around river km 925. This could be related to the construction of the side channel as the flow accelerates as it approaches the upstream end of the side channel, leading to bed erosion.

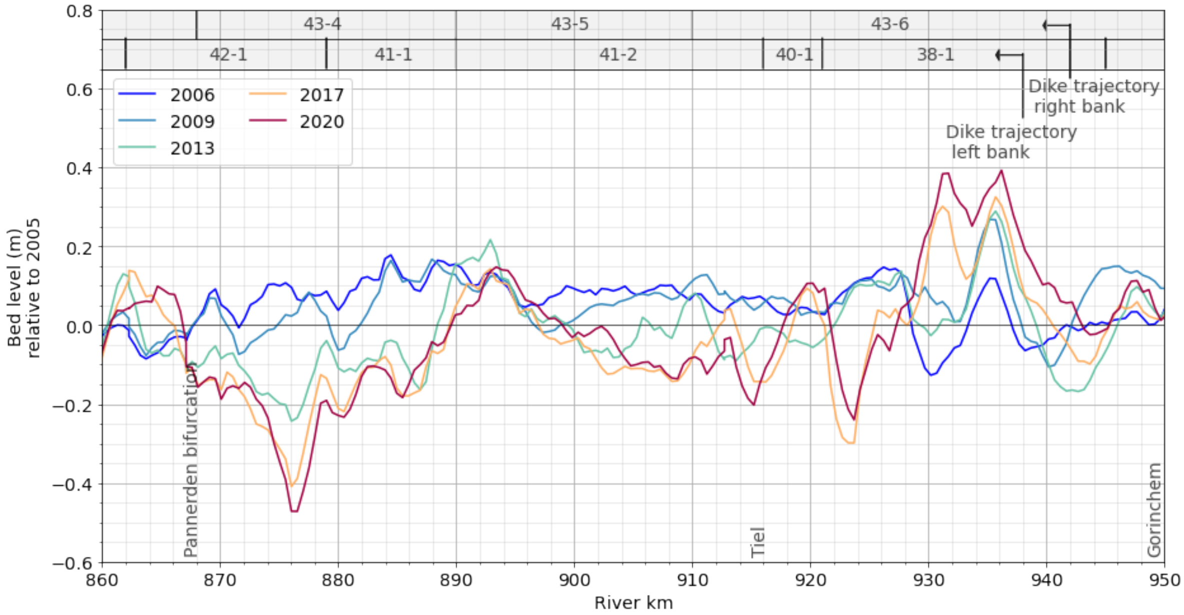


Figure 5.1: Bed level measurements of the Dutch Rhine in 2006, 2009, 2013, 2017 and 2020 relative to 2005. Dataset adapted from Ylla Arbós et al. (2021)

The variability in the bed level changes is shown in Figure 5.2 relative to 2005 and relative to the immediate previous year of each measurement. Large variability is observed around structures such as the fixed layers at km 875, 885, 925 due to erosion waves that originate at their downstream. Furthermore, a side channel around km 930 generates large variability in the bed levels due to sediment waves originating at upstream and downstream (Van Denderen et a., 2022). Similarly, other river structures and non-uniformities in the river geometry (Van Vuren, 2005) are expected to generate such sediment waves that contribute to the bed level variability. Moreover, the bed level variability is also influenced by regular river dredging, which takes place at the lower section of the Waal.

The standard deviation of the bed level changes relative to 2005 (Figure 5.2, top plot) varies spatially from 0.02 to 0.27 m. Bed level trends such as erosion and sedimentation trends influence the variability in the bed level changes. To reduce the influence of trends and isolate the variability around them, the yearly bed level changes relative to the immediate previous measurement are analyzed (Figure 5.2, bottom plot). Overall, the magnitude of the bed level variability is similar as in the previous plot; however, the variability around fixed layers (km 875, 885, 925) and river interventions (e.g. km 930) is considerably smaller. In general, the bed level change every year falls within the + / - 0.20 m range. The standard deviation of the yearly bed level changes varies spatially from 0.02 to 0.17 m. Averaged over the entire domain, the standard deviation is 0.06 m, which is in the same order of magnitude as previous studies in the Waal (Van Vuren, 2005).

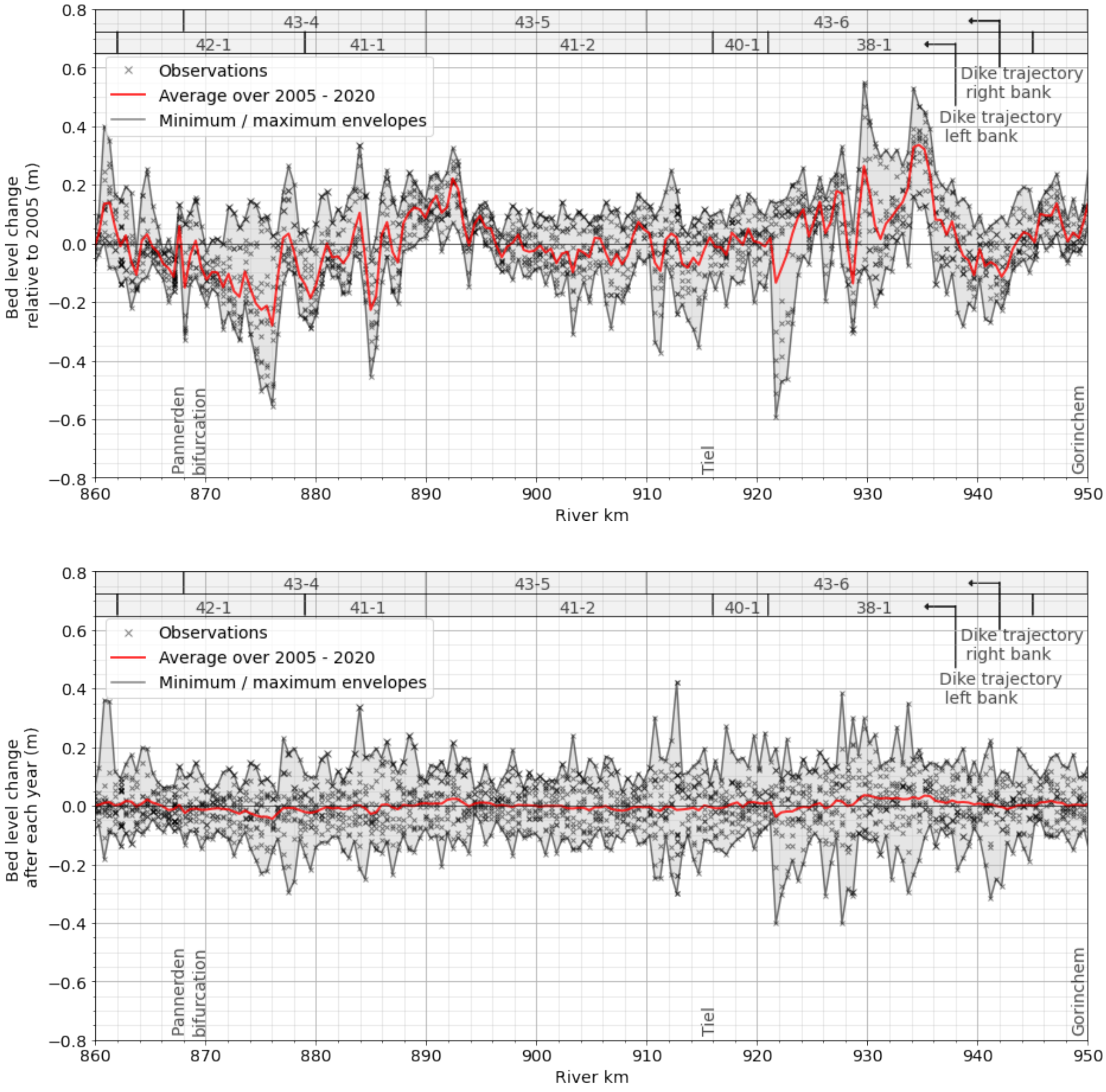


Figure 5.2: Spatial variability in bed level change relative to 2005 (top) and in bed level change after each year (bottom). Dataset: yearly bed level measurements from 2005 to 2020, averaged over 500 m, adapted from Ylla Arbós et al. (2021)

Figure 5.3 shows the bed level change averaged over the upper, middle and lower Waal as a function of time. Both the upper and middle Waal show a bed degradation trend; however, there exists a variability around this trend. For example, the bed levels in 2006 and 2009 lie above the bed levels in the corresponding previous years. This can be attributed to the bed level adjustment to erosion and sedimentation waves that migrate along the river and cause the bed level variability in Figure 5.2. In the lower Waal, a bed sedimentation trend is observed, as identified in previous studies (Van Denderen et al., 2022; Ylla Arbós et al., 2021; Van Vuren, 2005).

In the current safety assessment instruments, the most recent bed level measurement is used to calculate the hydraulic loads that will be adopted during the next 15 years (see Section 3.3.2). This assumption is conservative mainly in the upper and middle Waal, where incision trends are observed; however, at specific year measurements, slight bed aggradation up to 10 to 15 cm is observed. These aggradation observations have reduced their frequency and magnitude in the most recent years (Figure 5.3); therefore, it is expected that the probability of occurrence of significant aggradation in the upper and middle Waal is small in the near future. On the lower Waal, the bed level has shown an aggradation trend, up to 40 cm over the last 15 years, which could lead to higher hydraulic loads during a flood event. Therefore, the selection of a single bed level configuration could lead to an underestimation of the hydraulic loads in the near future based on the observed bed behaviour of the last 15 years.

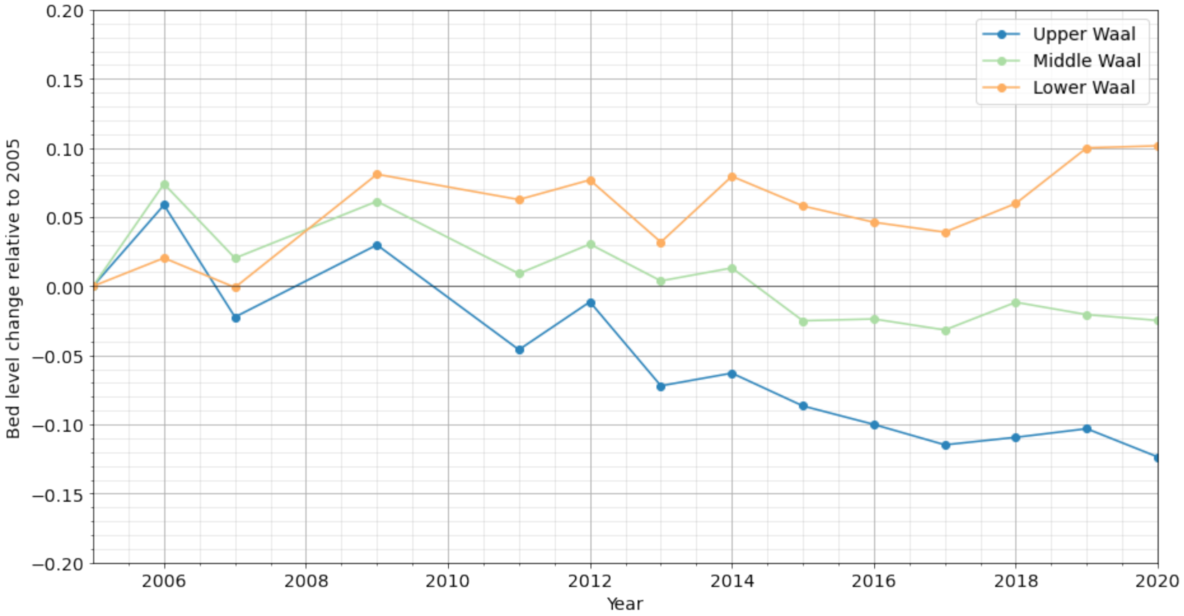


Figure 5.3: Bed level trend in time, averaged over the upper Waal (860 - 890 km), middle Waal (890 - 920 km) and lower Waal (920 - 950 km). Dataset: yearly bed level measurements from 2005 to 2020, averaged over 500 m, adapted from Ylla Arbós et al. (2021)

5.3.2. Hydraulic loads considering bed level variability

The water levels were calculated for the bed level configurations of each year. Figure 5.4 shows the spatial variability in the water levels for a peak discharge of 15000 m^3/s, whereas Figure 5.5 shows the water level trend in time averaged over the upper, middle and lower Waal at different discharge conditions. In general, the water levels show a decreasing trend in time in the upper and middle Waal, and an increasing trend in the lower Waal. It should be noticed that the trend in time is influenced by the timing of the measurement campaigns and the bed level variability at the scale within a year. The bed level variability due to dredging and sediment wave migration (see Section 5.3.1) cannot be fully captured at the yearly frequency of the bed level measurements. Therefore, the trend shown in Figure 5.5 is partly influenced by the instantaneous state of the river bed at the moment the measurement was taken.

Despite the general bed incision trend, yearly bed level changes may result in aggradation and in an increase of the hydraulic loads. For instance, the water levels in 2006 and 2009 are 0.02 to 0.04 m higher than in 2005 along the upper Waal. This yearly variability in the water level reduces after 2015, suggesting that the bed approaches a more stable state in the upper Waal. Therefore, it can be expected that these isolated sedimentation events will have a small probability of occurrence in the near future in the upper Waal.

The middle Waal shows a different behaviour, in which the water levels are more or less stable and have a slight decreasing trend. A period of one to a few years with high water levels is followed by another period with lower water levels. This shows a recovery behaviour of the bed level. Similarly to the upper Waal, the years 2006 and 2009 show bed sedimentation that lead to a slight increase in the water levels compared to the immediate previous year.

The lower Waal shows a similar stabilizing water level behaviour with an overall increasing trend. Over the analysis period, the water levels are the highest in 2020, with an increment in the order of 0.04 m compared to the 2005 situation. Despite the bed degradation observed at river km 925, the water level increases at this location due to the backwater curve influence of the higher water levels around km 935. In general, the water level variability maintains a similar behaviour to the bed level variability shown in Figure 5.3.

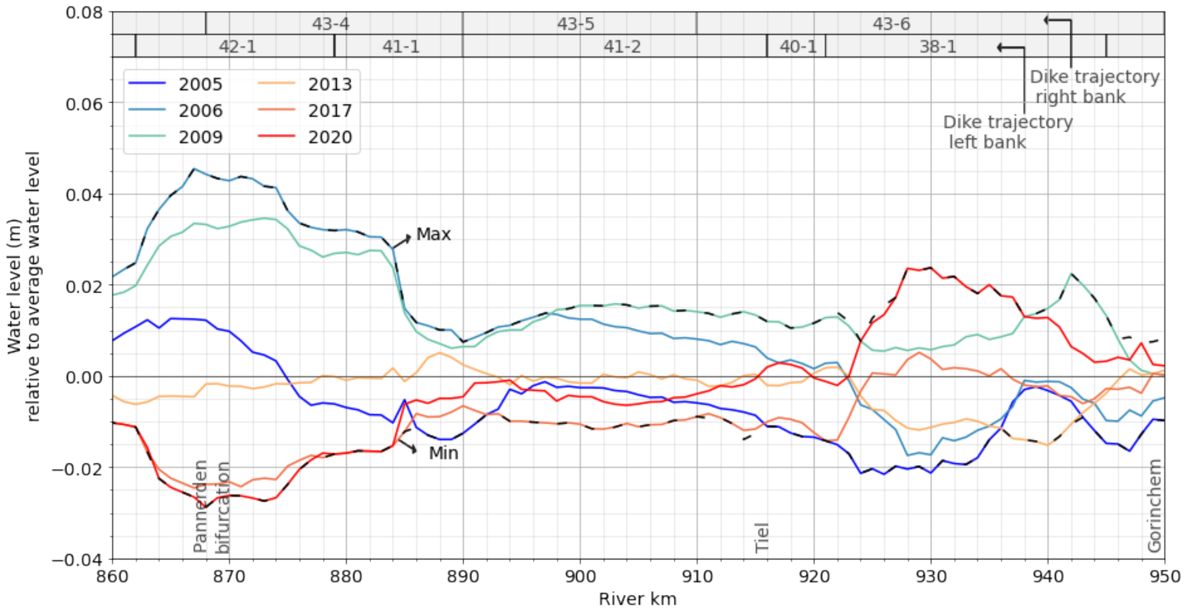


Figure 5.4: Water level relative to averaged water level during 2005 - 2020. Peak discharge at Dornick equal to 15000 m^3/s

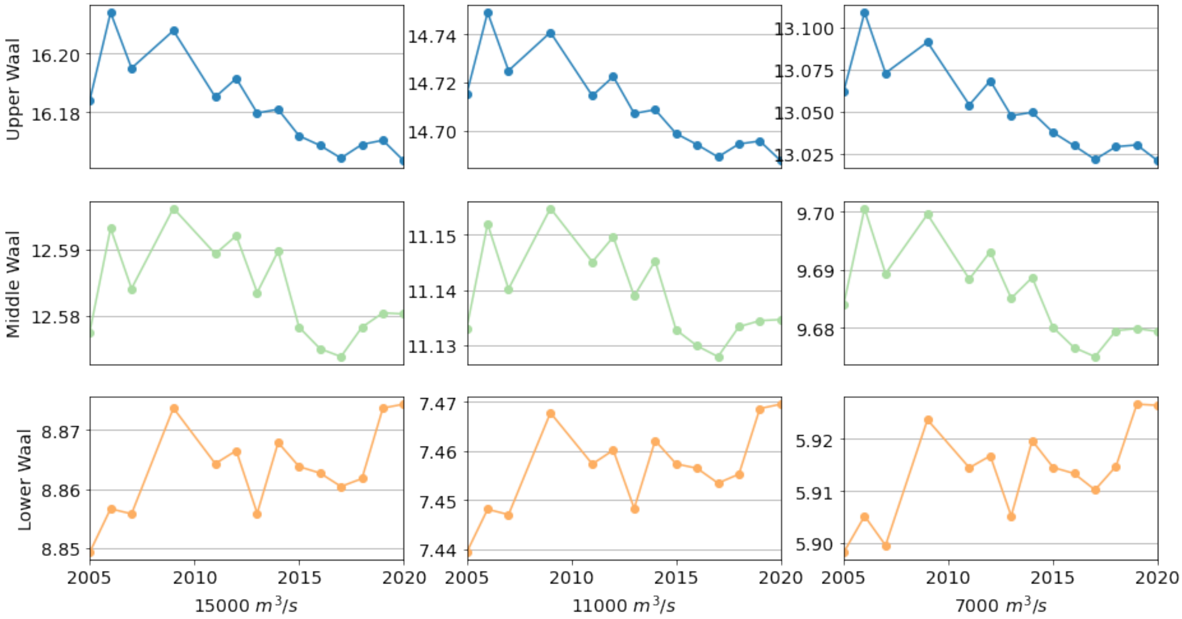


Figure 5.5: Computed water level trend in time. Water levels are averaged over the upper Waal (860 - 890 km), middle Waal (890 - 920 km) and lower Waal (920 - 950 km)

The average and maximum water level increment during 2005-2020 was calculated over the river km 920-940 (Table 5.1) for all the discharge conditions. As discussed in Section 4.3.3, the discharges above 7000 m^3/s are most relevant for flood safety in the lower Waal. In this range, the water level shows an average increment from 0.03 m to 0.05 m, and a maximum increment from 0.04 to 0.07 m. These increments in the water levels may be negligible compared to the long-term risk assessment (Chapter 4) and to the uncertainties within the safety standards derivation. However, they are significant compared to the hydraulic loads used within the safety assessment process. These loads are defined with a centimeter-accuracy (Van Vuren, 2005) and can have significant economical implications on reinforcement programs. Moreover, the water level variability in the order of 0.05 m is not negligible considering that the model uncertainty currently assumed around the water levels in the Waal is characterized with a mean of 0 m and standard deviation of 0.15 m (see Section 2.1).

The impact of large-scale bed level variability on flood safety can be incorporated via the model uncertainty used in the current assessment instruments. A conservative approach is to add a positive mean of 0.05 m into the model uncertainty for the water levels along the lower Waal, while maintaining the hydraulic loads calculation based on the fixed-bed assumption in the middle and upper Waal. This would account for the water level increments observed between the 2005-2020 period in the lower Waal. The short-term variability in the water levels cannot be clearly identified based on the yearly measurements. An analysis based on more frequent bed level measurements is required to better estimate the variability around the water levels as a standard deviation that could be incorporated into the model uncertainty.

As discussed in Chapter 4, the water discharge partitioning at the Pannerden bifurcation also impacts the hydraulic loads in the bifurcates. This can be partially attributed to the bed level changes around the bifurcation, but has not been considered in this analysis, as we focus on the influence of bed level changes alone. However, Chowdhury et al. (2022) shows that the discharge partitioning is uncertain and varies every year. This could lead to larger and smaller changes in the water levels compared to the ones calculated in this chapter.

Discharge (m^3/s)	Average	Maximum	Discharge (m^3/s)	Average	Maximum
2000	0.07	0.11	11000	0.04	0.06
4000	0.09	0.13	12000	0.04	0.05
5000	0.08	0.12	13000	0.04	0.05
5600	0.08	0.12	14000	0.03	0.05
6200	0.05	0.08	15000	0.03	0.04
7000	0.05	0.07	16000	0.03	0.04
9000	0.05	0.06	17000	0.03	0.04
10000	0.04	0.06			

Table 5.1: Average and maximum water level increment (m) during 2005 - 2020, averaged over km 920 - 940

5.3.3. Failure probability considering bed level variability

The amplification of the failure probability was calculated based on the upper and lower limits of the water levels between 2005-2020 (Figure 5.6). In the upper Waal, an average increment of 5% and 10% in the failure probability at the dike sections levels are observed for macro stability and piping, respectively. It should be noted that these increments in the failure probability are associated to isolated water level increments in the year 2006 and 2009. More recent years show an overall reduction in the failure probability, in line with the bed incision and water level decreasing trends in time.

In the middle Waal, the average increment accounts to 3% and 5% for macro stability and piping, respectively; and in the lower Waal, to 5% and 10%, respectively. As mentioned in Section 5.3.2, this increment in the failure probability is not significant compared to other uncertainties in the long-term risk assessment, which can have an impact up to a factor 3. However, the short-term increasing trend in the failure probability can have a significant influence on reinforcement programs.

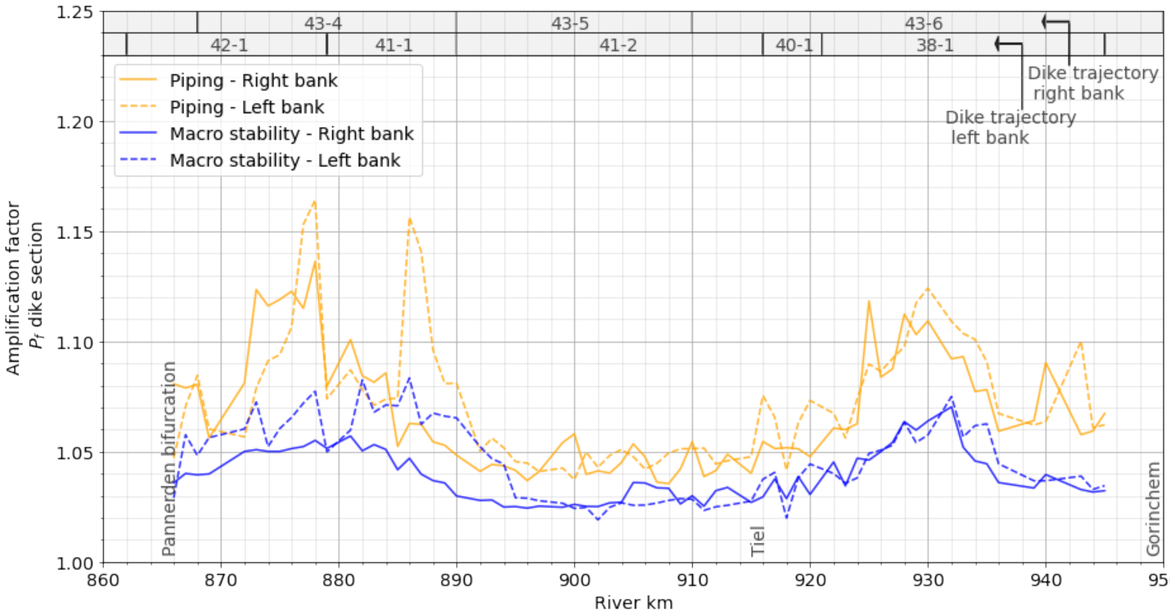


Figure 5.6: Maximum amplification factor during 2005 - 2020 of the failure probability at the dike section level

5.4. Conclusions

An analysis of the recent 15 years bed level measurements in the Dutch Rhine shows that the hydraulic loads can increase in time, despite the general incision trend. At the upper and middle Waal, this was associated to isolated bed aggradation events in 2006 and 2009; however, more recent years do not show this behaviour. In the lower Waal, an increasing trend of the water levels is observed due to a bed aggradation trend.

The fixed-bed assumption is expected to yield conservative hydraulic loads in the upper and middle Waal in the near future. On the contrary, the hydraulic loads in the lower Waal can be underestimated by an order of 0.05 m when assuming a fixed-bed. This has an impact on the failure probability at the dike section, estimated by an increment of 5% to 10%, considering the macro stability and piping failure mechanisms.

The uncertainty in the water levels due to the bed level variability can be incorporated into the current safety assessment instruments via the model uncertainty parameters of its hydrodynamic model. A conservative consideration is to include a positive mean of 0.05 m in the model uncertainty of the water levels in the lower Waal. This assumption would account for the possible increments in the water levels, based on the recent past behaviour of the bed levels. An analysis with more frequent bed level measurements is required to better estimate the variability in the water levels as an additional standard deviation into the model uncertainty.

6

Discussion

Significance of the case study results

In the short-term flood safety analysis, it was found that the yearly bed level variability in the Waal generally falls within a + / - 0.20 m interval based on bed level measurements from 2005 to 2020. The water levels and the failure probabilities were estimated to vary by 0.05 m and by 10%, respectively, due to this bed level variability. These changes are small and have little influence on the safety standards derivation process. However, they have significant impacts on investment costs within reinforcement programs in the Netherlands, for which the hydraulic loads are defined with a centimetre-accuracy (Slootjes, 2016; Van Vuren, 2005). Moreover, an increment of the water levels in an order of 0.05 m is significant compared to the model uncertainty in the current safety assessment instruments, where the water level uncertainty is represented by a standard deviation of 0.15 m.

Compared against the natural variability in river discharge and extreme discharge events, bed level changes add little variability. For this reason, the river discharge is the main uncertain variable for the analysis of river-dominated systems in the Netherlands. Its uncertainty has been quantified via probabilistic methods in order to better estimate the hydraulic loads. In this sense, bed level variability has relevant implications on the hydraulic loads calculations as it interacts directly with the thoroughly assessed river discharge. Therefore, an increment in the water levels in the order of 0.05 m is significant compared to the level of analysis that the river discharge statistics undergo in the current safety assessment process.

In the long-term flood safety analysis, the morphodynamic modelling results adopted (Ylla Arbós et al., 2023) project bed incision in the upper Waal and bed sedimentation in the lower Waal. These bed level changes were estimated to yield an average increment in the water levels in the lower Waal up to 0.15 m in 2050 and up to 0.30 m in 2100. The failure probabilities were estimated to increase by 40% and 90% in 2050 and 2100, respectively. These increments are significant compared to the safety standards, which are defined in classes with increments of factor 3, equivalent to increments of 200%.

Within the safety standards derivation process (see Section 2.1.2), the failure probability has been found to have neglectable influence on the economical optimal level of protection criterion compared to other uncertain variables such as the future economical scenario and the cost uncertainties (Slootjes, 2016). However, the failure probability has important implications on long-term investment costs. Moreover, other criteria such as the loss of life estimation could be more significantly impacted by changes in the failure probability. This could lead to an impact in the safety standards derivation, as both individual and societal minimum protection levels have to be ensured along with the economical criterion.

The water level variability due to bed level changes has also been studied against other uncertainty sources. It has been found that long-term river discharge increase due to climate change has a higher impact on the water levels compared to bed level changes (Hiemstra et al., 2022). The former variability is in the order of 0.40 m; the latter, in the order of 0.10 m by the year 2050. This impact on the water levels due to bed level changes is smaller than the one obtained in this thesis, which are in the order of 0.15 and 0.20 m by 2050. However, the bed level changes considered in (Hiemstra et al., 2022) were simplified and an order of magnitude smaller than those adopted in this thesis. Therefore, bed level changes may have larger impacts than estimated by Hiemstra et al. (2022) and be comparable to the impact of river discharge increase due to climate change.

The case study results in this research can also be reflected on considering other uncertainty sources. For instance, the representativeness of the bed level measurements and the discharge partitioning at the Pannerden bifurcation add large uncertainties and affect how the hydraulic loads and failure probabilities investigated here. This is discussed in the following paragraphs.

Representativeness of the bed level measurements and morphodynamic modelling results

As described in Section 5.3.1, sediment waves of different spatial scale travel along the river bed at different celerities. Therefore, the river bed is a dynamic compound of multiple migrating sediment waves, which can take months, years or decades to propagate. In this context, the yearly bed level measurements analyzed in this research are single snapshots in time of the dynamic bed level. The temporal variability in the bed level evolution may not be captured at the yearly frequency of the measurements. Thus, the bed level variability and the results derived from it are influenced by this uncertainty in the bed level representation.

From the bed level and water level analysis carried out in Section 5.3, a trend in time can be identified for different river sections in the Waal. On the contrary, the variability around this trend is less certain at the yearly frequency of the bed level measurements. It is recommended to analyze this shorter term variability based on more frequent bed level measurements, at monthly to trimestral frequencies. It is expected that the overall trend in time in the bed level and water level will not change. However, a more frequent analysis can provide a more precise estimation of the standard deviation around the water levels due to bed level variability.

In the long-term flood safety analysis, limitations of the morphodynamic model affect the representativeness of future bed level changes. For example, the morphodynamic model contains uncertainties in parameters such as the sediment transport formula, nodal point relationship at the bifurcations, sediment grain-size, among others. These variables are defined by best estimates based on calibration; however, their future uncertainty influences the river bed response obtained from the morphodynamic model. Moreover, the model developed by Ylla Arbós et al. (2023) considered maintenance dredging in the lower Waal only until 2025. This assumption may overestimate the sedimentation in the lower Waal after 2025, assuming that dredging maintenance will continue to take place for navigational purposes. It was observed that the bed level changes in the downstream end impacted the water level variability at upstream sections due to a backwater effect. Therefore, it is essential to focus on the dredging practices representation at the lower river sections in the morphodynamic model.

It is recommended to define the long-term morphodynamic models and scenarios in agreement with the long-term plans in the Netherlands, such as those developed within the Integrated River Management Programme (Ministry of Infrastructure and Water Management, 2023). Within this programme, long-term measures are outlined regarding the maintenance and raising of the river bed channels in the Dutch Rivers. It is important to consider these major river interventions to better represent the future situation. Nonetheless, it is still essential to define scenarios around the expected situation to account for the large uncertainty in long-term morphological modelling.

Uncertainty in discharge partitioning at Pannerden bifurcation

The uncertainty in the discharge partitioning at the Pannerden bifurcation is not quantified in this research, which focuses on the impact of bed level variability on the hydraulic loads. Nonetheless, both types of uncertainty can be interrelated as the bed level configuration around the bifurcation influences how much water and sediment is distributed over the branches. This interrelation was neglected in the case study application of this thesis; however, the variability in the discharge partitioning can enhance or diminish the effects of the large-scale bed level variability on the hydraulic loads.

As described in Chapter 4, the ongoing incision trend in the upper Waal leads to a reduction in the future hydraulic loads. However, the incision in the upper Waal near the Pannerden bifurcation also leads to a higher intake of discharge into this branch and to a relative increase in the hydraulic loads.

Both mechanisms have opposite effects on the hydraulic loads and could result in a net increment in the future water levels. More research is recommended to define scenarios for the long-term morphodynamic evolution of the Pannerden bifurcation and study the future discharge partitioning during high flows.

The discharge partitioning is also variable within a yearly basis and it can be quantified based on discharge measurements (Chowdhury et al., 2022). In the short-term flood safety analysis (Chapter 5), a fixed discharge partitioning ratio was assumed; however, its variability can amplify or diminish the effects calculated due to bed level changes alone. It is recommended to study the relationships between the bed level variability and the discharge partitioning ratio at the Pannerden bifurcation based on past bed level and discharge measurements.

The discharge partitioning at the Pannerden bifurcation can be defined in different manners. On the one side, it can specified as a fixed ratio, a yearly variable ratio or a ratio following a probability distribution function. These representations show increasing complexity, but can provide a more clear picture of the impacts of the discharge partitioning variability on the hydraulic loads. On the other side, the water discharge partitioning can be calculated from hydrodynamic models. In this case, the bed level configurations of both bifurcates are modelled in order to compute the discharge distribution by solving the equations of flow motion. This approach is more time consuming, but is able to capture more physical processes influencing the water discharge distribution. However, it is important to notice that the partitioning during extreme design conditions is highly uncertain as these conditions have not yet been observed (Mosselman, 2012).

Relevance of other morphological features

This investigation focused on large-scale bed level changes; however, other morphological features have an impact on flood safety (see Section 2.2.2). For example, bedform evolution under extreme conditions has been found to have important implications on the hydraulic loads. The effects of bedforms on flood safety can be superimposed to the effects of large-scale bed level changes as these two morphological processes are independent. For instance, the bedform geometrical changes are not expected to change due to domain-wide sedimentation or erosion. Therefore, the large-scale bed level framework proposed in this thesis can be complemented by the existing or future findings on bedform geometry changes under extreme conditions.

Bed level degradation can also lead to weakening of flood defences foundations, thus affecting their strength and the failure probability. Given that these processes are dependent on geotechnical local conditions, it was not feasible to analyze them at the large-scale framework proposed in this research. However, I recommend to analyze them on a case by case basis. As the weakening of the flood defences foundation does not affect the hydraulic loads, they can be complemented to the proposed framework. Their impact on the failure probability can be significant in the upper Waal, where there exists an incision trend. They can have important economic implications for the reinforcement of dike foundations to counteract the effects of incision.

The sediment load during flooding events can also impact the flooding damages estimation on infrastructure and people. This is particularly relevant, considering that the damage functions represent one of the main uncertainty sources in the safety standards derivation process (Westerhof et al., 2022). This morphological feature does not affect the hydraulic loads, but has an overall impact on the flood risk estimation. It can be complemented into the proposed framework in this research. It is recommended to investigate the impacts of all these morphological features, besides large-scale bed level changes, on flood safety in the Netherlands.

Flexibility of the morphodynamic approaches in the proposed framework

In the short-term flood safety, I recommend to incorporate the analysis of past bed level behaviour into the hydraulic loads calculation within the safety assessment process. This approach can be flexible, depending on the development of morphodynamic models in the Netherlands. Past bed level behaviour and morphodynamic models can be integrated to better estimate the behaviour of the river bed during the next 12 to 15 years. However, the incorporation of morphodynamic models would increase the complexity of the overall process. This research finds it justified to estimate the near future behaviour based on the recent past, considering that previous studies have shown that the past bed level analysis provided reasonable results compared to fully probabilistic morphodynamic modelling results (Van Vuren, 2005). It may be necessary to include morphodynamic modelling within the short-term framework when drastic morphodynamic changes can be expected in the near future; for instance, due to recent large river interventions or due to significant changes in the river bed maintenance policy.

In the long-term flood safety, I recommended to include several deterministic morphodynamic models to quantify the variability of future bed level changes via scenarios. It is not recommended to apply stochastic models alone, since they are not suitable for epistemological uncertainty sources such as future river management. However, stochastic morphodynamic models could be incorporated with deterministic models. For instance, the stochastic modelling technique for discharge variability applied by Van Vuren (2005) could be performed under different deterministic scenarios for the future river management or other epistemological variables. This would increase the representativeness of the forecasts in the long-term, but increase the complexity of the modelling process. For a first attempt on integrating large-scale bed level changes into the long-term flood safety framework, I recommend to adopt deterministic morphodynamic models only. Thorough discussion should follow on the definition of the morphological scenarios.

Incorporating order-of-magnitude bed level changes into hydrodynamic models

A decoupled method was used to incorporate long-term bed level changes into higher resolution hydrodynamic models. Long-term morphodynamic models are usually simplified to capture the large-scale and long-term bed level changes in an efficient manner. In doing so, the model becomes less suitable for hydraulic applications, such as the estimation of water depths and water levels (Chavarrias et al., 2020). Therefore, a separate hydrodynamic model is required in order to assess the hydraulic loads during extreme events.

A method was developed to incorporate the long-term morphodynamic results into a hydrodynamic model suitable for flood safety assessment. The order-of-magnitude relative bed level changes of the morphodynamic model were applied into the hydrodynamic model main channel geometry. Thus, the more detailed schematization of the latter was conserved, while including the large-scale bed level changes. This approach allowed to decouple the more simplified morphodynamic model from the more detailed hydrodynamic model schematization. This method can be further automated as a rapid tool for the assessment of hydraulic loads under several morphological scenarios.

Upscaling the framework to other river-dominated systems

The proposed framework was applied to the Waal branch only; however, it could also be applied to the other Rhine branches in the Netherlands, as well as to the Meuse river. For the short-term flood safety analysis, the intensive monitoring of the river bed levels in the Netherlands enables its assessment under the proposed framework. When studying the Rhine branches as a system, it is important to analyze the interactions at the bifurcations and their influence on the discharge and sediment distribution. Depending on the results at the entire system level, adjustments can be proposed on the model uncertainty at the river system, branch or dike trajectory level. For the long-term flood safety analysis, long-term morphodynamic models of the other river branches in the Netherlands are required. Such models have been developed under the Integrated River Management Programme in the Netherlands (Chavarrias et al., 2020) and can be used to estimate future large-scale bed level changes.

The proposed approach can be applied to river systems outside of the Netherlands. Scarce bed level measurements can be a limitation to analyze the past bed level behaviour. In this case, morphodynamic models can be incorporated to compensate for this limitation in the short-term flood safety analysis. In less engineered river systems, morphological processes related to changes in the river planform may become more relevant. For instance, morphological changes in the floodplains, bank erosion and channel widening are more important in non-channelized rivers. These processes should be taken into account in morphodynamic models of such river systems, where the bed level variability alone is less representative of the river morphological behaviour. Lastly, the flood safety frameworks in other countries mostly focus on the hydraulic loads alone; therefore, some effects of river morphology on the flood defences strength and the flooding damages may be overlooked. It is important to identify this when applying the proposed framework to river systems with different flood safety approaches than in the Netherlands.

7

Conclusions and recommendations

7.1. Conclusions

How has the river bed changed over the last decades in the Dutch part of the Rhine?

The Dutch Rhine shows a general incision trend in the upper Waal and a sedimentation trend in the lower Waal over the last decades. The bed level shows high spatial and temporal variability due to migrating sediment waves with different length scales and wave celerities. The average bed level has been estimated to vary within a + / - 0.20 m range due to this short term variability during the period 2005 - 2020. The bed level variability has been found to be larger around river structures such as fixed bed layers and side channels, as they induce large gradients in the sediment transport capacity. It is expected that the bed tilting trend in the Waal will continue in this century, based on morphodynamic modelling studies up to the year 2100.

How can river bed level variability be incorporated into the current flood safety framework in the Netherlands?

The current flood safety framework in the Netherlands is composed of two elements with fundamentally different characteristics and objectives. On the one side, the safety standards are derived from a long-term flood risk assessment, with projections up to 50 and 100 years into the future, which does not consider long-term river morphological changes. I propose to incorporate morphodynamic modelling via scenarios as these are suitable for representing complex epistemological uncertainties related to the long-term river response in the Netherlands. Key long-term sources of uncertainty in the Netherlands include future river discharge, sea level rise, river maintenance and bifurcation evolution. I propose to translate their variability via scenarios into long-term bed level variability, hydraulic loads variability and failure probability variability within the safety standards derivation process.

On the other side, safety assessment instruments have been developed to uniformly assess all flood defences in the Netherlands in shorter-term cycles, every 12 years. I propose to incorporate the analysis of recent past bed level behaviour to estimate its impacts on flood safety in the near future. Both the trend and variability around the bed level changes should be assessed and translated into water level changes. I propose to update the hydraulic loads model uncertainty used in the assessment process if significant negative implications on flood safety due to bed level changes are found. This approach is simple compared to morphodynamic modelling approaches, which is in agreement with the cost-effective nature of the safety assessment instruments in the Netherlands.

How are the hydraulic loads affected by river bed level variability compared to the current fixed-bed assumption?

For the long-term flood safety analysis, the river bed level variability is obtained from existing morphodynamic models of the Rhine up to the year 2100. The future water levels in 2050 and 2100 reduce over the upper Waal compared to the fixed-bed assumption due to the bed incision trend. Over the lower Waal, they increase when considering bed level changes in 2050 and 2100. In this lower river section, the fixed-bed assumption could lead to an underestimation of the water levels in the order of 0.15 m and 0.30 m in the year 2050 and 2100, respectively. It should be noted that the morphodynamic modelling scenarios applied in this analysis do not consider river maintenance after the year 2025, which is expected to yield results in the upper spectrum of possible future hydraulic loads.

For the short-term flood safety analysis, yearly bed level measurements from 2005 to 2020 are analyzed. The water levels calculated under these bed configurations show an overall decreasing trend in the upper Waal and an increasing trend in the lower Waal compared to the fixed-bed assumption. Over the lower Waal, the water levels have been estimated to increase by an order of 0.05 m due to bed sedimentation. The temporal variability in the bed levels are not fully captured at the annual frequency of the measurements, which does not allow to quantify the water level variability around the trend.

In general, the fixed-bed assumption in the current flood safety framework is a conservative, or safe, assumption for the hydraulic loads calculation in the upper Waal. However, it may underestimate the future hydraulic loads in the lower Waal and impose adverse conditions on flood safety. Increments in the water levels in the order of 0.05 m are relatively small. Nonetheless, they are significant compared to the accuracy level of the hydraulic loads defined for the safety assessment instruments, and can have important economical implications on dike reinforcement programs.

How is the failure probability of a flood defence affected by river bed level variability compared to the current fixed-bed assumption?

The failure probability varies accordingly to the water level changes considering bed level variability. The failure probability is computed for the piping and macro stability failure mechanisms at the dike section level along the Waal. In the long-term analysis, smaller failure probabilities are calculated over the upper Waal compared to the fixed-bed assumption. On the other hand, larger failure probabilities are obtained in the lower Waal, which can increase on average up to to 40% in 2050 and up to 90% in 2100 compared to the fixed-bed assumption. In the short-term analysis, the calculated failure probabilities show a reduction in time due to bed incision and water level decrease over the upper Waal. Over the lower Waal, an increment of 5 to 10% in the failure probability was calculated.

Similar to the impact on the water levels, the fixed-bed assumption is a conservative assumption for the calculation of failure probabilities in the upper Waal. However, bed incision can also lead to a reduction in the strength of the flood defences due to weakening of their foundations. This can have an opposite effect to the reduction in the hydraulic loads and lead to a net increase in the failure probability. Over the lower Waal, the fixed-bed assumption can lead to an underestimation of the failure probability by up to a factor of 2 in the long-term. This is a significant change, considering that the safety standards are defined by failure probabilities classes every factor of 3. It should noted again that the morphodynamic modelling scenarios applied in the long-term analysis do not consider river maintenance after the year 2025, which is expected to result in higher failure probabilities than in a scenario in which the river bed is regularly maintained in the lower Waal.

7.2. Recommendations

I recommend to incorporate morphodynamic modelling of the Dutch Rhine into the long-term flood risk assessment in the Netherlands to account for river bed level changes in the next 50 to 100 years. It is important to collaborate with the Integrated River Management Programme in order to account for morphological scenarios that include river interventions within the national planning policy in the Netherlands. The morphological scenarios should also include different scenarios for future river discharge, sea level rise, river maintenance and morphological evolution at river bifurcations.

Furthermore, I recommend to investigate the impact of large-scale bed level changes on the Meuse River and on the other Rhine branches in the Netherlands following the proposed short- and long-term flood safety frameworks. A system analysis is required for the Rhine branches, with a particular focus on the the role of the river bifurcations on water and sediment distribution.

Also, I recommend to analyze the past bed level behaviour at a more frequent measuring interval, at the order of months, in order to better identify the temporal variability of the bed level. Following this analysis at the system level, a trend and variability in the water levels can be attributed to large-scale bed level changes. I recommend to incorporate these findings into the model uncertainty of the water levels within the safety assessment instruments in river-dominated systems.

Finally, I recommend to investigate other morphological processes that influence flood safety, such as bedform evolution during extreme discharges, the bed degradation at the flood defences foundation, the suspended sediment load in the flood wave and the effects of bifurcation instability on the water discharge partitioning. These are relevant uncertain processes in the Dutch rivers that can enhance or diminish the effects of large-scale bed level variability on flood risk. These processes can be complemented to the flood safety frameworks proposed in this research.

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Appendix A - Hydrodynamic modelling considerations

Discharge statistics at Dornick

The discharge statistics at Dornick were based on the GRADE results, as considered in the current flood safety framework. To simplify the probabilistic calculations for the failure probability, a continuous probability distribution function was defined to represent the upstream discharge statistics. A Generalized Extreme Value (GEV) distribution was found suitable with shape, location and scale parameters equal to 0.15, 5300 m^3/s and 2200 m^3/s, respectively (Figure A.1).

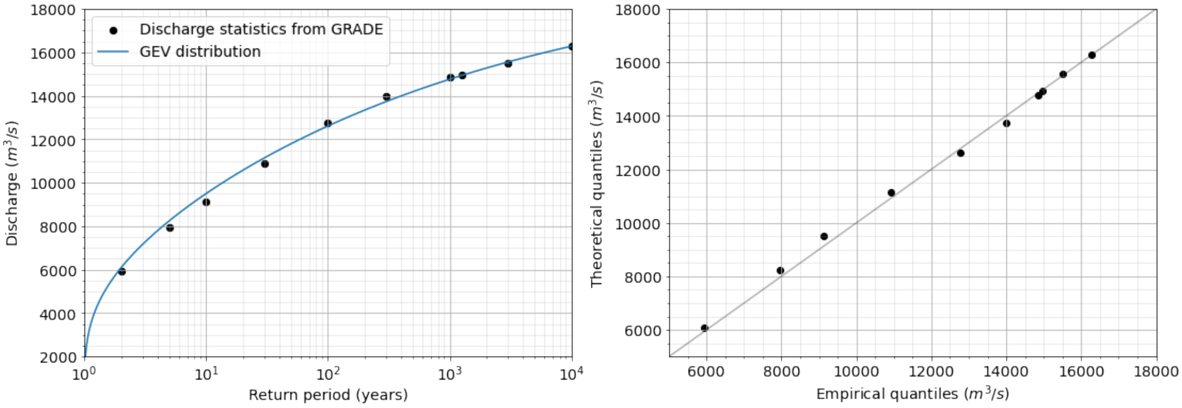

Figure A.1: Discharge statistics at Dornick. Left: GEV distribution compared to GRADE statistics. Right:Q-Q plot

Based on the GEV distribution, discrete discharge values were defined to carry out the hydrodynamic simulations, while maintaining the discharge statistical properties (Figure A.2). The discharge values were selected so that the overall shape of the probabilistic distribution is conserved and so that linear interpolation between the discrete values would not create undesired distortion.

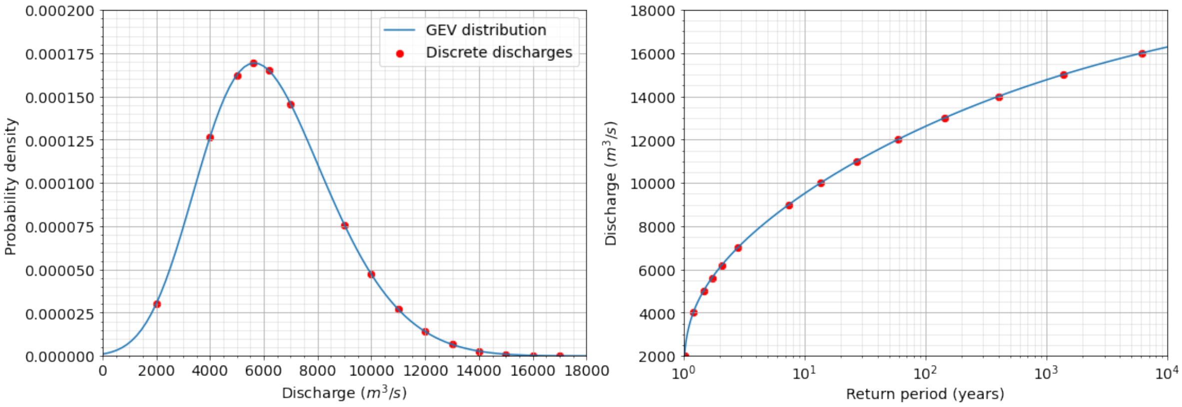

Figure A.2: Left: Discrete discharge values in the probability density function. Right:Discrete discharge values at the return period scale

Influence of bed level changes on the downstream boundary condition

The water elevation - discharge relationship at the downstream boundary condition may be affected by bed level changes. This boundary condition depends on the hydrodynamic processes downstream of the model domain. Since it is uncertain how the long-term morphology will change in this estuary area, it is uncertain how the downstream boundary condition will be affected.

A sensitivity analysis was performed to quantify the effect of changes in the downstream boundary condition on the hydrodynamic model. The downstream boundary condition is updated and tested considering the water level change at river kilometer 934. At this location, the bed aggradation is approximately the same as in the downstream boundary condition (Figure 4.3) for the 2100 base model scenario. It is assumed that the downstream boundary condition shifts towards 0.25 m higher elevations, as the water level increases by this amount at kilometer 934 for the 2100 base model. All morphological scenarios are tested under this condition for a peak discharge of 15000 m^3/s.

The difference in the water levels when including a positive shift of 0.25 m at the downstream boundary condition is dictated by a backwater curve effect (Figure A.3). It is observed that the influence is less than 0.05 m upstream of kilometer 940, and less than 0.02 m upstream of kilometer 920. These magnitudes are relatively small compared to the overall water level increment observed in Figure 4.3. It is considered reasonable to neglect the long-term effects of bed level changes on the downstream boundary condition. Further research is recommended to investigate the long-term morphological response in the estuary system.

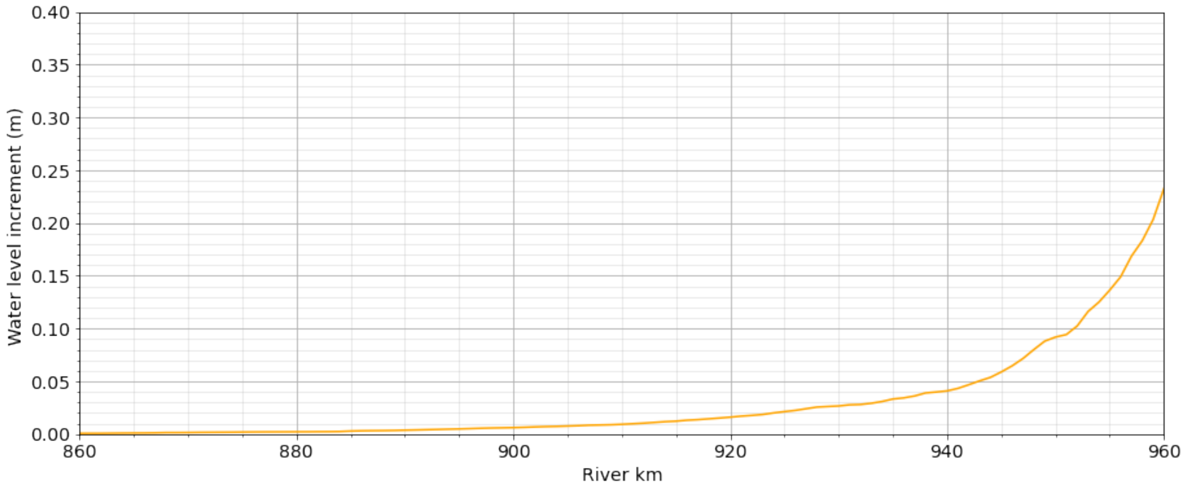

Figure A.3: Water level increment due to a positive shift of 0.25 m in the elevation - discharge relationship of the downstream boundary condition