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Prediction of Culvert Failure

A desktop study of water-driven culvert failure in Soknedal using a developed method

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Master's thesis in Hydraulic Engineering

Candidate: *Hege Merete Kalnes*

Subject: **Prediction of culvert failure**

1. Background

Failure situations at culverts are a major problem for the operation of infrastructures such as road and railways. Multiple different factors contribute to such failures, and factors such as maintenance, blocking, exceedance of dimensional flood and flaws in the design may be problematic to culverts. In Klima2050 there is a work package that will develop methods for handling such situations and for assessing the risk of such infrastructure in a future with changing land use and climate. This thesis will be part of this work, and have as its main goal to develop a method based on fault tree analysis to predict culvert failure and to put these together into software. The software can be used to evaluate failure in the future given changes in factors that influence the culvert. The work will be based on a framework outlined in the project task written the autumn of 2017.

2. Work tasks

The main work will be to build up a fault tree for culverts and to put together and develop the analytical methods for the different nodes in the tree. Then, they will be implemented as software that can be used to evaluate failure situations for a selection of situations where we have observations. The work can be divided into three main tasks:

1. Setup of fault tree based on the project task:
    a. Determine methods for the tree's different nodes and necessary data to drive them.
    b. Collection of data for testing and setup of the methods that are included in the fault tree.
    c. Consider what parts of the tree can be implemented with the knowledge and methodology we have access to, and what should be done with simpler methods and where future developments are necessary.
2. Implement the tree from 1) in the form of a computer program.

    a. Encoding of methodologies as specified.
    b. Retrieve some "cases" that may be used to test the methodologies. These must be obtained from known failure situations from existing data, such as BaneNor from Soknedalen.
    c. Document test-runs for the methods that have been implemented.
3. Use software develop in 2) on a set of example catchments to show how this tool can be used to assess the risk of culvert failure.
4. Evaluate the uncertainties in methodologies that are used and developed.

3. Guidance, data and information

Supervisor of this thesis is Professor Knut Alfredsen at the Department of Water and Environmental Engineering, NTNU. The work is carried out in collaboration with SINTEF through Mehdi Ahmadi and will be linked to the work of Klima 2050 work package 2. The candidate is responsible for collecting, checking and using data. Help from the abovesaid or others must be referred to in the report.

4. Report

Structure and layout of the report is important. Assume that the target group is senior technical staff. The report must contain a summary that gives the reader information about the background, procedure and the main results. The report must have a table of contents and reference list. The reference list must be formatted according to an existing standard.

Data that is collected must be documented and delivered in digital form.

The format of the report must follow the standard at NTNU. All figures, maps and images included in the report must be of good quality with plain text on the axis and the legend.

The candidate must include a signed signature that claims that the work presented is her own and that all contributions from other sources are identified through references or other means.

The thesis deadline is 11th of June 2018.

Department of Water and Environmental Engineering, NTNU

Knut Alfredsen,

Professor

Abstract

The risk connected to water-related hazards on roads and railways is becoming more acute in Norway. A significant maintenance backlog combined with climate change and land modification and -intervention has increased the probability for such events to occur, and the importance of the road- and railway infrastructure is increasing with a growing Norwegian economy. This work focuses on the hazard connected to water-driven culvert failure, and is a part of the research center Klima 2050's endeavor to achieve better risk estimation for stormwater management in small catchments.

The main objective of this work is to develop a method to predict culvert failure. Failure is defined in the work as exceedance of the capacity given by the headwater that is considered safe. The method is based on using a constructed fault tree and estimates the failure occurrence from flood return periods. It is aimed to be practically applicable for risk assessments and feasible as a desktop study, primarily using available information from public Norwegian databanks and services. It is found that methods chosen to estimate capacity and flood has to be of low complexity to achieve the aim of practicality. Three simple methods are used to estimate capacity, the NIFS-formula is used to estimate flood return periods and the effects of climate- and land cover change is considered through using constant percentages of change in flood size.

Three scientific questions are established in order to provide a reference point in the development of the method and to explore its capabilities as a desktop study for risk assessments. They deal with how often culvert failure occurs under possible failure modes, the effects of climate- and land cover change on the occurrence, and how it can be reduced to an acceptable level. In answering the questions and testing the method which is developed, the work provides a case study of eight culverts in Soknedal which have previously failed and led to damages on a railway line. The findings show that the culverts will not fail unless they are severely blocked. This can occur due to slides, which are relatively common in Soknedal, or if the maintenance is inadequate.

The uncertainties in the risk estimation provided by the method are potentially large and need to be further investigated. Independently of whether the method is deemed useful and the uncertainties acceptable, this work provides a comprehensive overview of the risk connected to culverts and how it can possibly be modelled.

Sammendrag

Risikoen knyttet til vannrelaterte farer på veier og jernbaner blir stadig mer alvorlig i Norge. Et betydelig etterslep på vedlikehold kombinert med klima- og arealbruksendringer har økt sannsynligheten for at slike farer oppstår, og viktigheten til vei- og jernbaneinfrastrukturen øker med en voksende norsk økonomi. Dette arbeidet fokuserer på faren forbundet med feil ved kulverter under flom, og er en del av prosjektet til forskningssenteret Klima 2050 for å oppnå bedre risikoestimering innen overvannshåndtering i små nedbørfelt.

Hovedformålet med dette arbeidet er å utvikle en metode for å forutsi feil ved kulverter. Feil er her definert som overskridelse av kapasiteten der oppstrøms vanndybde er på et nivå som ansees trygt. Et feiltre har blitt konstruert, og metoden bruker dette feiltreet for å estimere hvor ofte feil kan opptre gjennom returperioder for flom. Metoden er utviklet med et mål om å være praktisk anvendelig for risikovurderinger og å være gjennomførbart som en skrivebordsstudie som bruker tilgjengelig informasjon fra offentlige norske databaser og tjenester. For å oppnå det praktiske målet er metodene valgt for å estimere kapasitet og flom av lav kompleksitet. Tre enkle metoder brukes til å estimere kapasitet, NIFS-formelverket til å finne returperioder for flom, og virkningen av klima- og arealbruksendringer er betraktet gjennom prosentvis endring i flomstørrelse.

Tre vitenskapelige spørsmål er etablert for å gi et referansepunkt i utviklingen av metoden og for å teste dens evne som en skrivebordsstudie for risikovurderinger. De omhandler hvor ofte feil oppstår ved mulige feilmoder, hvordan dette påvirkes av klima- og arealbruksendringer og hvordan det kan reduseres til et akseptabelt nivå. Ved å besvare disse spørsmålene som en test av metoden, presenterer arbeidet et case-studie om feil ved kulverter i Soknedal. Den undersøker åtte kulverter som har tidligere feilet og ført til skader på en jernbanelinje. Funnene viser at kulvertene ikke vil feile med mindre de er blokkert. Dette kan skje hvis skred opptrer, som er relativt vanlig i Soknedal, eller hvis vedlikeholdet er utilstrekkelig.

Usikkerhetene i risikoestimeringen gitt av metoden er potensielt store og må undersøkes ytterligere. Uavhengig av om metoden anses nyttig og usikkerhetene akseptable, gir dette arbeidet en omfattende oversikt over risikoen forbundet med kulverter og hvordan den kan muligens modelleres.

Preface

The master's thesis *Prediction of Culvert Failure* is written by Hege Merete Kalnes during the spring of 2018 and corresponds to a workload of 30 credits. It is the final endeavor as a student attending the five-year long degree program Civil and Environmental Engineering at NTNU in Trondheim.

The thesis is a continuation of the project task *Framework for Predicting Culvert Failure During a T-year Flood* with a larger focus on finding, evaluating and implementing methods. The tasks have predominantly dealt with studying literature and collection and evaluation of data. The work has proved both challenging and educational, as it encompasses many topics that are brought together in an attempt to form an innovative product.

Professor Knut Alfredsen at NTNU has provided guidance throughout the work and his contribution as both a supervisor and supporter has been greatly appreciated. The work is done in cooperation with Klima 2050 through research scientist Mehdi Ahmadi at SINTEF Building and Infrastructure, who has contributed with helpful discussion and suggestions. I wish to express gratitude for these contributions and to friends and family for keeping me confident and positive in my work.

Hege M. Kalnes

Hege Merete Kalnes

Trondheim, June 2018

Table of contents

List of figures

List of tables

1 Introduction

1.1 Water-related hazards for roads and railways

Infrastructures and buildings exposed to floods and slides can result in large costs to society due to structural damage and potential loss of health or life. Roads and railways are among the infrastructures that are vulnerable to floods and slides since their construction involves human intervention in natural drainage paths (Myrabø et al., 2016). Stormwater management is important to minimize the negative effects of the intervention. Measures in the form of several drainage system components must be in place to ensure that stormwater is collected upstream the road or railway and safely lead to natural downstream waterways. This entails that the water should not take unwanted paths and thereby avoiding operational disturbances and/or structural of damage to the road/railway itself or third parties. When slides occur, the affected drainage systems will have decreased capabilities to perform their function, so the combination of slide and flood can be critical. Further, their inability to perform can cause slides in embarkments or downstream slopes, giving cascading effects (Norem et al., 2016).

There is a significant maintenance backlog for roads and railways in Norway, which has led to drainage system components often being deteriorated and sometimes undersized. Combined with climate change and land-modification and -intervention, this has led to an increase in the frequency of hazard events connected to floods and landslides (Myrabø et al., 2016). The importance of a well-functioning road- and railway infrastructure has increased concurrently with a growing Norwegian economy, since such infrastructure is essential to public welfare and a competitive business sector (Meld. St. 33 (2016-2017)). Using a technical risk perspective, risk is the combination of probability and consequence of an undesired event (Aven and Renn, 2010). More frequent water-related hazard events and growing importance of roads and railways means, consequently, an increase in risk and as such a need for better risk treatment.

This need has been acknowledged; in 2015, the center for research-based innovation hosted by SINTEF Klima 2050 was started up. Its main goal is to reduce societal risk though climate adaption of buildings and infrastructure, where its work is divided between four main research areas. One of the areas is stormwater management in small catchments, where Klima 2050 aims at providing better risk estimations for flooding of infrastructure (Time, 2016).

The responsibility of designing and maintaining the road and railway infrastructure, including stormwater management, lies with the Norwegian Public Roads Administration (Norwegian: Statens vegvesen, SVV) and Bane NOR, formerly the Norwegian National Rail Administration

(Norwegian: Jernbaneverket, JBV). The overall responsibility of prevention of flood damage lies with the Norwegian Water Resources and Energy Directorate (Norwegian: Norges vassdrags- og energidirektorat, NVE). The three institutions provide guidance and requirements to stormwater management of roads and railways in Norway that, in result, represents a national standard. All three institutions are members of Klima 2050 and will be responsible for the implementation of the improved risk estimations for water-related hazards in the road- and railway infrastructure.

1.2 The importance of functioning culverts

One of the most important components in the road- and railway drainage system is culverts. Culverts are closed water conduits with open inlets and outlets smaller than 2.5 meters that lead water from the upstream to the downstream side of a road or railway Their capacity and design is critical for the road- and railway integrity since they go through the embarkments, giving a larger damage-potential than structures that are laid parallel. Further, their lack of capacity and proper design is one of the most common causes of unwanted events that occur (Norem et al., 2016). Such events can be flooding of the road or railway and/or third parties, reduced carrying capacity, slides and collapse of the embarkment. In Norway, it can also lead to issues with frost heaving and icing (Thordarson et al., 2011). Figure 1.1 depicts a recent example of the how large the damage potential of culvert failure can be.

Figure 1.1 Embarkment slide on the railway line Nordlandsbanen on the 22nd of April after a blocked culvert lead to rising of the upstream water level (photo: Sivertsen, 2018).

An insufficient culvert capacity is often due to the culvert being blocked or clogged, which has become both more probable and severe with the maintenance backlog. An area in Norway with such problems is Soknedal. A case study performed by Vauclin (2017) showed that out of eight studied cases of culvert failure on the railway line Dovrebanen in Soknedal, none of the culverts had too small dimensioning capacity, indicating that they were blocked when failure occurred.

1.3 Purpose, scope and limitations

Increasing maintenance backlog, climate change and land-modification and -intervention calls for the risk of culvert failure being better understood so that the risk of failure for both existing and new culvert can be decreased. This work aims at providing such an understanding and is part of Klima 2050's undertaking to achieve better risk estimation for flooding of infrastructure. It focuses on the probability-aspect of risk in the form of predicting how often a given culvert will fail.

The primary objective of this work is to develop a method to predict culvert failure based on fault tree analysis. The method is limited to only consider water-driven failure, not structural, and can thus use flood return periods to estimate how often failure can occur through a comparison of capacity and incoming flood. The effects of climate- and land cover change is also addressed to be able to evaluate future failure scenarios.

The culvert failure prediction method is developed with the goal of being a practical tool in risk assessments of culverts in Norway and to be feasible as a desktop study that can be performed with the available information from public Norwegian databanks and services. An encoded version of the method in the form of an Excel workbook is also developed to be able to quickly attain results. The workbook is intended to be user-friendly and thereby not require having to read this work for it to be used.

The purpose of this work is to use the developed method to answer the following scientific questions in a case study of culverts in Soknedal. The questions are established with two intentions. The first is to provide a reference point in the development of the method. The second it to explore the capabilities of the method for risk assessments in an area with occurring culvert failure.

- How often does culvert failure occur under the possible failure modes?
- What effect has climate- and land cover change on the occurrence of culvert failure?
- How can the occurrence of culvert failure be reduced to an acceptable level?

The method is to predict culvert failure, not to estimate failure probability which was the initial objective of this work. The reason for abandoning this objective is that there are many different factors that can contribute to culvert failure and finding expected conditions and their probability to occur for a given culvert simultaneously as a critical flood is a complex task. Early in the process, this proved to be too time-consuming and complex. The failure modes are therefore treated as known inputs based on evaluations This makes the method more applicable for exploration of possible failure-situations rather than probability-estimation.

Klima 2050 emphasize that stormwater management has to take on a more holistic approach where the interrelationship between water infrastructure has to be considered (Time, 2016). The water infrastructure in roads and railways is, however, a complex system that consist of several components. To create a holistic system analysis that includes all the components is beyond the scope of this work, and the culvert is treated as an independent component. The contribution of other components, both in terms of capacity and incoming water, is rather given as inputs that can be explored.

A framework for predicting culvert failure was developed during the fall by Kalnes (2017), which includes a fault tree for culvert failure. The culvert failure prediction method can be viewed as an extension of the framework, as many of its elements can be applied. However, it is important to note that this is an independent work. The framework will therefore be scrutinized as opposed to being used directly without alterations.

1.4 Structure of work

The main objective of this work is to develop a method to predict culvert failure. The theory and literature chosen to be investigated is consequently based on what is deemed necessary to be able to develop and understand the method. However, the purpose of this work is to answer the scientific questions in the case study of Soknedal. The structure of this report is therefore built up as that of a traditional report, where the developed method is treated as the tool to attain results in the case study:

> **2 Theory and literature study:** The subject of risk is first investigated, where theory behind important concepts within risk and its relevance for culverts is presented followed by a literature study of current risk assessment methods on culverts and a description of the framework proposed by Kalnes (2017). As water-driven culvert failure largely deals with the exceedance of capacity, this issue is the next to be presented. Both the flood- and capacity element of the issue is investigated, where

theory behind causes of a reduced capacity is also included. The effects of climate- and land cover change that are relevant to the issue of exceedance follows. Methods for flood- and capacity estimations is then explored, and the chapter ends with a review of available culvert-related data.

3 Material and method: The risk methodology is first established, where the failure definition is given and a fault tree for culvert failure is constructed. The method for predicting culvert failure is then established by selecting which elements in the fault tree that can be modelled and which of the reviewed methods is expedient to use with the available data and purpose of the method. A short description of how the method is encoded in Excel and tested is also given. Finally, the case study is presented, including acquirement and evaluation of data and how the scientific questions are answered using the developed workbook through three analyses.

4 Results: Results from the three analyses are presented and a summation given to provide a clear answer to the scientific questions.

5 Discussion: The results from the case study is shortly discussed to uncover what the results imply in more practical terms. As the culvert failure prediction method is the main product of this work, a longer discussion of the feasibility of the method as a tool in risk assessments is given, including an assessment of uncertainty in its results.

6 Conclusion and recommendations: The findings from the case study and the discussion about the performance and usage of the culvert failure prediction method is summed up in a conclusive way that reflects the introduction of the work. This includes recommendations for further work.

2 Theory and literature study

2.1 The concept of risk and how it applies to culverts

For the culvert failure prediction method to be a tool in risk assessments it needs to consider important concepts within risk, the risk connected to culverts and current assessment methodology. The subject of risk and how it applies for culverts is therefore presented in this section, including a summary of the framework developed by Kalnes (2017).

2.1.1 The technical risk perspective in risk management

Risk can be defined in many ways and the definition used depends on the person viewing the risk and the purpose one has when studying it. When dealing with risk management, it is expedient to have a technical risk perspective; risk is the combination of probability and consequence of an undesired event and can be expressed through probabilities and expected values. This entails that there are clearly defined causes to the undesired event, thereby allowing the effect of avoiding or modifying the causes to be modelled. It is also common to establish risk acceptance criteria in order to assess the risk and need for risk treatment in a defined context (Aven and Renn, 2010).

With a technical risk perspective, one often views the object of analysis as a system. The system performs a required function, and the inability to perform this function is defined as system failure. To acquire the necessary information about the system to make assessments and decisions, a system analysis is performed, where the fault tree technique is one of the best-known methods to identify the possible ways a system may fail (Vesely et al., 1981). The *Fault Tree Handbook NUREG- 0492* (Vesely et al., 1981) published by the US Nuclear Regulatory Commission presents detailed material on fault tree construction and evaluation and is largely considered as one of the best sources for performing a fault tree analysis.

Risk management is central for planning on tactical level of Infrastructure Asset Management (IAM), and deals with the identification, analyzation, evaluation and treatment of risk (Ugarelli, 2017). IAM is a set of strategies used to preserve and extend the service life of public infrastructure assets, with focus on maintenance, rehabilitation and replacement (Cagle, 2003). Risk management in Norway is usually performed in the form of risk- and vulnerability analyses (Norwegian: ROS-analyser), which consists of five phases (DSB, 2017):

1. Description of the object of analysis
2. Identification of possible unwanted events
3. Assessment of risk and vulnerability (probability/consequence/uncertainty)

4. Identification of measures to reduce risk and vulnerability
5. Documentation of analysis and how it affects the object

In the third phase, the risk is usually presented in a risk-matrix and placed in a category of acceptable, unacceptable or the area between where the risk should be decreased if reasonably possible (DSB, 2017).

Probability	**Consequences**		
	Small	Moderate	Large
High	🟨	Unacceptable	Unacceptable
Medium	Acceptable	🟨	Unacceptable
Low	Acceptable	Acceptable	🟨

Figure 2.1 Example of risk-matrix.

2.1.2 The risk connected to culverts

Functioning culverts are important for the structural integrity of the road- and railway-infrastructure and the quality and safety of traffic. The main water-related risks connected to culverts deals with erosion, flooding and reduction of the load bearing capacity.

There are three main types of erosion that can occur in the embankment around the culvert, illustrated in Figure 2.2. The first is local scouring at the outlet of culverts, which can occur with large outlet water velocities. It can give formation of scour holes, causing undercutting and slope instability that can lead to the embankment sliding out. The second is internal erosion, which is caused by water flowing though granular soils that are not self-filtering and can lead to piping and following formation of sinkholes. The piping may occur due to water seeping into the embankment from the headwater or in and out of the culvert from cracks. The third is scouring of the downstream embankment caused by overtopping flow, which can progress quickly and lead to formation of a void or complete washout of the embankment (Jenssen, 1998). The types of erosion described will cause permanent damages to the road/railway, and can prove a danger to life and health when they progress quickly in a flooding situation or is allowed to progress over time without being dealt with (Norem et al., 2016).

Water on the road- and railway due to flooding can reduce drivability and safety. If the water takes unwanted paths and reaches areas that are not designed for large amounts of water, the damages can be substantial. The load bearing capacity of the embankment will become reduced if it’s saturated, exposed to freezing and thawing and if fine erosion-particles are washed into it. This can occur if the headwater stands against the embarkment, which in itself can lead to the embarkment sliding out (Norem et al., 2016).

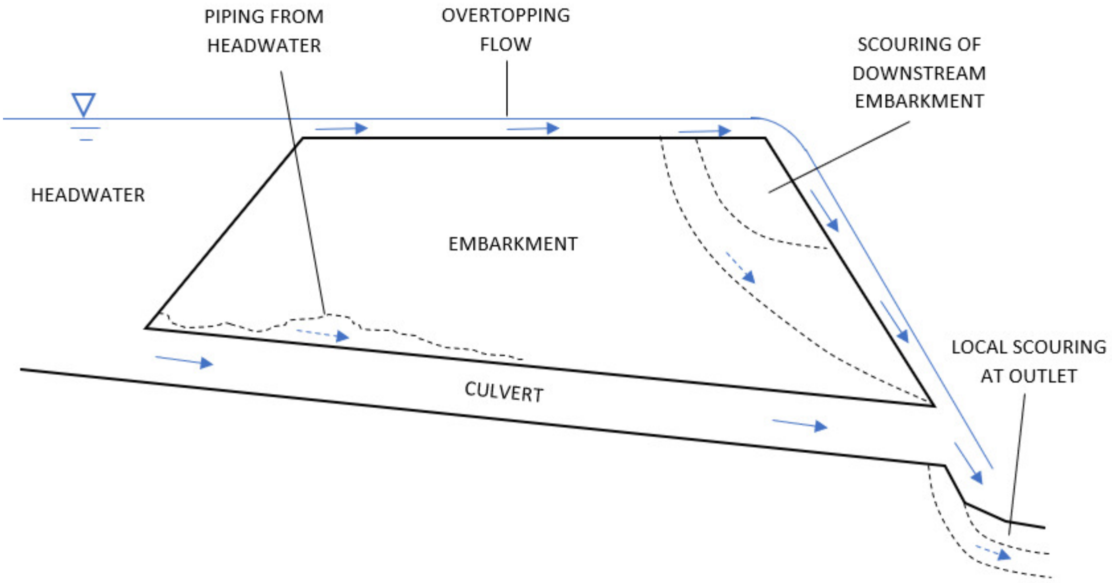


Figure 2.2 Cross-sectional illustration of possible erosion-situations at culverts- note that only scouring of downstream embarkment requires the illustrated overtopping flow.

2.1.3 Current Norwegian risk assessment methods for culverts

The guidelines for stormwater management provided by the Norwegian Public Roads Administration (SVV), Bane NOR and the Norwegian Water Resources and Energy Directorate (NVE) include guidelines for how risk assessments should be performed. The following is an investigation of these guidelines, given by or in cooperation of these three institutions.

Risk acceptance criteria for culverts are given by the accepted return-period of the dimensioning flood it should be able to safely lead away. The return-period is 200 years for railways and 100 and 200 years for roads with and without traffic detour possibilities. The resulting flood is often referred to as the 200- or 100-year flood (Eidsvig, 2014). The return period gives the statistical average number of years between each time the flood-size is exceeded (Holmqvist, 2010). For floods smaller or equal to the dimensioning, the road or railway should not be closed for a longer period and no serious damage befall them (Norem et al., 2016). Bane NOR requires that new culverts are designed with a climate-factor of 1,2 times the 200-year flood, while SVV only requires the factor to be above 1,0 (Eidsvig, 2014).

SVV operates with a three-level risk- and vulnerability analysis based on the classification of acceptable and unacceptable risk (Berggren et al., 2015). The analysis is directly applied to culverts, where the approach is its entirety is presented a report by Thordarson et al. (2011) published by SVV. The first level consists of a simple analysis based on desktop studies of culverts, surrounding environments and maintenance routines to identify areas or specific culverts that are expected to cause disruption of traffic in a flooding situation. Based on a qualitative assessment of the probability for this to occur and its consequence, the culverts are taken into the second level if they don't have an acceptable risk. At this level, an extended analysis is performed based on simple calculations of design capacity, meaning the capacity of an open and functioning culvert, and dimensioning flood in addition to condition assessments from inspections. Culverts that have sufficient residual capacity of 50% or more and is in technically good condition are deemed to have an acceptable risk, including those that can be taken into the accepted category with simple technical measures. Those deemed to have an unacceptable risk are subject to a special analysis in the third level, with detailed capacity and flood calculations that focuses on the effect of climate change and includes calculations on the effect of proposed measures. After the complete three-level risk- and vulnerability analysis is performed, a culvert should have a risk classification of acceptable, reasonably acceptable or unacceptable. In terms of maintenance and rehabilitation this means, respectively, that the need for measures are none, simple in the form of cleaning and unblocking and extensive in the form of repair, replacement or excavation (Thordarson et al., 2011).

Bane NOR does not have their own guidelines or specific methods to perform risk- and vulnerability analyses. They often use external work-force to perform such analyses that uses their own established methods (Berggren et al., 2015). A report by Bane NOR (2014) on capacity estimation and condition assessment of culverts on the railway line between Garli and Støren does however provide some insight to how they can perform risk assessment on culverts. Simple estimation methods are used to find design culvert capacity and dimensioning flood and a priority class from 1 to 3 is given based on lacking capacity and condition assessments from inspections. The priority class gives how soon measures must be taken, and culverts that have sufficient capacity and don't need measures are not given a priority class.

Condition assessments include assessment of damages, blocking from sediments, debris and ice, erosion at-inlet and outlet and other flaws or deficiencies that may cause a reduced capacity and/or prove a danger to structural integrity (Thordarson et al., 2011). According to regulations, visual inspections of culverts should be performed every 12 months for railways (Bane NOR, 2014b) and a simple every 12 months and a more thorough every 5 years for roads (SVV, 2014b). If the degree of blocking exceeds 20% of the culvert's cross-section, measures have to be taken for both railways and roads (Bane NOR, 2014b; SVV, 2014b)

Culverts are also assessed in a more holistic manner with floodway analyses, often combined with registrations of water-related damages, to uncover vulnerable points in the road and railway infrastructure. If such a point is a culvert and/or caused by a failing culvert, one should perform a more detailed risk assessment of the culvert in question (Norem et al., 2016).

2.1.4 Framework for predicting culvert failure

A framework developed by Kalnes (2017) proposes how to predict culvert failure in response to a flood with a given return period, referred to as the T-year flood. It is applicable for two levels of planning in stormwater management; the flood-situation and the extreme situation. The flood-situation is the situation for which the culvert is designed for, where it shall be able to lead away water up to the dimensioning flood without relying on alternative floodways (Norem et al., 2016). The extreme-situation applies for when the culvert's design criteria are exceeded, where the water should not take *unwanted* alternative floodways in order to avoid large economical and societal costs (Norem, 2016).

The framework uses a technical perspective of risk, and followingly views the culvert as a system that performs the function of safely leading away water. The definition of culvert failure is consequently that the culvert is not able to safely lead away water. To provide a technical specification to the term *safely*, for which the T-year flood can be compared to, requirements to the headwater is established. It is assumed that the structural safety of the road/railway only depends on headwater level, and universal requirements are given for the framework to be applicable for multiple types of culvert designs and characteristics. In the flood-situation, the required headwater level is set to the top of the culvert to avoid water going into alternative floodways and the embarkment being damaged by the headwater. In the extreme-situation, the required headwater level is set to the top of the road/railway level to avoid overtopping and following flooding and dangerous erosion on the downstream side of the embarkment. For these headwater levels the culvert will have a critical capacity that, if exceeded, will give culvert failure.

The prediction of failure is based on the usage of a developed fault tree that is created with guidance of the *Fault Tree Handbook NUREG-0492* (Vesely et al., 1981). The fault tree analysis is performed to find all the credible ways the culvert might fail, and using the established technical definition, this translates to how the critical capacity may be exceeded.

The concept of failure effects, -modes and -mechanisms is used and the deductive accroach of the fault tree method. The first cause found is exceedance of design capacity, meaning the capacity of an open and functioning culvert, which is both an effect, mode and mechanism. Further, modes that can cause the effect of reduced capacity is explored. It is established that a reduced capacity can be due to downstream flooding, blocking and deterioration. Downstream flooding is both a mode and mechanism. Blocking is divided into modes according to the reason behind it; landslide, icing, woody debris and sediment accumulation, and possible mechanisms behind these are listed. Deterioration in the form of damage and deformation of the culvert is given as a failure mode without specifying the mechanisms behind it. The idea is to first check exceedance of design capacity, which will give automatic failure. Then, by looking at which failure modes that applies for the culvert and T-year flood, the critical capacity is adjusted to the modes that will occur, and culvert failure occurs if the reduced capacity is exceeded.

The framework is to be used in risk assessments, and by finding the smallest flood that gives culvert failure one can estimate failure probability. It is, however, recommended that a review of the framework is done to reveal weaknesses and/or lacking elements.

The framework does not propose how the culvert capacity nor the T-year flood should be calculated, but it is recommended that the methods should reflect the quantity and quality of available data.

2.2 Exceedance of culvert capacity

Water-driven culvert failure largely deals with an exceedance of capacity, meaning that the incoming flood is larger than the capacity of the culvert and consequently causing water to take alternative ways. This section looks into the flood- and capacity element of this issue. The incoming flood is first investigated followed by why the design capacity may be insufficient and how a culvert's capacity may be reduced. The causes behind a reduced culvert capacity is divided according to the categories given by Kalnes (2017); downstream flooding, blocking and deterioration.

2.2.1 The incoming flood

Culverts receives water from smaller catchments in the form of runoff from rain and/or snow melt. In small Norwegian catchments, it is usually the short and intense rainfall-events that dominates and results in the larger floods. The combination of rain and snow melt can in some catchments also result in quite large floods, especially in mountainous-areas (Stenius et al., 2014). The response of the catchment to rain and/or snow melt depends on its characteristics.

A larger and flat area with bodies of water and vegetation will have a slower response and resulting smaller flood-peaks due to attenuation of water, as opposed to a small and steep area with impervious surfaces of bare mountain or asphalt. The amount of precipitation a catchment receives is also important; more intense and frequent rain results in saturated soil, giving faster and larger responses (Stenius et al., 2015).

The culvert may receive water from neighboring catchments. The lacking capacity of a culvert can be lead to a downstream culvert through intended and unintended floodways that can be found though performing a floodway analysis. An example of intended floodways is open and deep ditches, which are common for railways and roads outside of urban areas. (Norem et al., 2016). Culverts may also receive water from a neighboring catchment if the water in a stream changes direction. This can occur on alluvial fans due to rapid erosion and sedimentation or when stream are blocked by slides, resulting in water being led away from the intended culvert (Clarkin et al., 2006).

2.2.2 Insufficient design capacity

Guidance and rules for designing culverts exists in handbooks for both roads and railways, with emphasis on the importance of finding the dimensioning flood as the basis of choosing design and size to give the necessary capacity. Exceedance of design capacity should therefore not occur for floods smaller than the dimensioning (Norem et al., 2016). One does not, however, have to go far back to find contradictory guidance to today's standard. Up until 2011, both SVV and Bane NOR operated with smaller dimensioning return-periods. SVV used dimensioning return-periods of 25 to 100 years instead of to the current 100 or 200 years (SVV, 2005; SVV, 2011), and Bane NOR used 50 years instead of 200 years (Bane NOR, 2011). Some culverts may also have been placed without consideration of dimensioning flood. Requirements to minimum dimensions can be used as the only design requirement for catchments smaller than 1 ha for roads (SVV, 2014c), and some culverts may have been built with too small capacity (Bane NOR, 2014b). This will give a culvert with insufficient design capacity with respect to the dimensioning flood given by today's standard.

2.2.3 Reduced capacity due to downstream flooding

The outlet of culverts can become submerged due to downstream flooding, which can give a reduced capacity. Downstream flooding can occur due to hindrances in the downstream floodway or due to flood in a downstream body of water (Norem et al., 2016). The latter is relevant for roads and railways that are laid in shorelines or along rivers, whose height should be set above the downstream water-level for a 200-year flood. It is possible for such floods to reach areas that are not directly connected to the river though culverts or bridges across embarkments, and such areas are referred to as low-points (NVE, 2008).

In larger Norwegian catchments to rivers and lakes it's mainly rain or a combination of rain and snow melting that results in the largest floods, with the exception of inland, mountainous and glacier areas where snow melting is dominating (Stenius et al., 2014).

2.2.4 Reduced capacity due to blocking

The reduction of a culvert's cross-section will decrease its capacity, and there are several objects that can block a culvert unless measures are in place to avoid it and if maintenance is inadequate. The causes behind blocking can roughly be divided into sediment accumulation, slides, erosion of downstream river, wood lodging and ice problems (Thordarson et al., 2011).

Sediment accumulation is the is the gradual build-up of sediments in front of the culvert and in its barrel. Blocking of culvert inlet can occur if water-velocities become reduced and there is no or inadequate upstream sediment pond to collect the sediments. The latter will also give sediment accumulation in the barrel for culverts that are not steep enough to achieve the water velocities required for it to be self-cleansing (Norem et al., 2016). Sediment accumulation in the barrel will give an increase of roughness in addition to reducing the cross-section, further reducing the capacity (Bradley et al., 2005). The source of sediments is erodible soils in the catchment and/or streams, and the amount of sediment that is eroded dependents of the steepness of the catchment and flow-discharges it experiences (Thordarson et al., 2011).

Slides involve the movement of material downwards in the terrain, often in a mix with water, whose outlet may reach culverts and followingly block its inlet. The main types of slides in Norway occur in the form of snow, slush, soil, debris and rock, whose composition is illustrated in Figure 2.3. Many of them are triggered by heavy or long-lasting rain or intense snowmelt, and the risk of slides increases with the steepness of the terrain (NVE, 2014). Culverts for stream-crossings are especially exposed to flow-like slides, that is, debris- and slush-flows which consists of water and about 40-70% sediments. Such slides can be initiated in or near by streams, where they are mixed and carried with the water down to the culvert. Culverts can also be the cause of slides if either their location or lack of capacity leads water outside existing streams to areas with no natural erosion protection (SVV, 2014a). The occurrence and size of debris flows and soil slides depends on the thickness, layering and grain size distribution of soils. The presence of vegetation in the catchment is also an important factor, as it increases soil strength and reduces erosion. Slides can be avoided by increasing the slope stability though different measures depending on the type of slide, and their consequence reduced by leading the masses away or stopping them with embarkments, channels, nets or sedimentation pools (NVE, 2014). Slides from the embarkment itself may also block a culvert's inlet or outlet. This can occur in instable slopes where there are no headwalls to stabilize the embarkment and the culvert's ends are not projecting from embarkment (Bane NOR, 2014b).

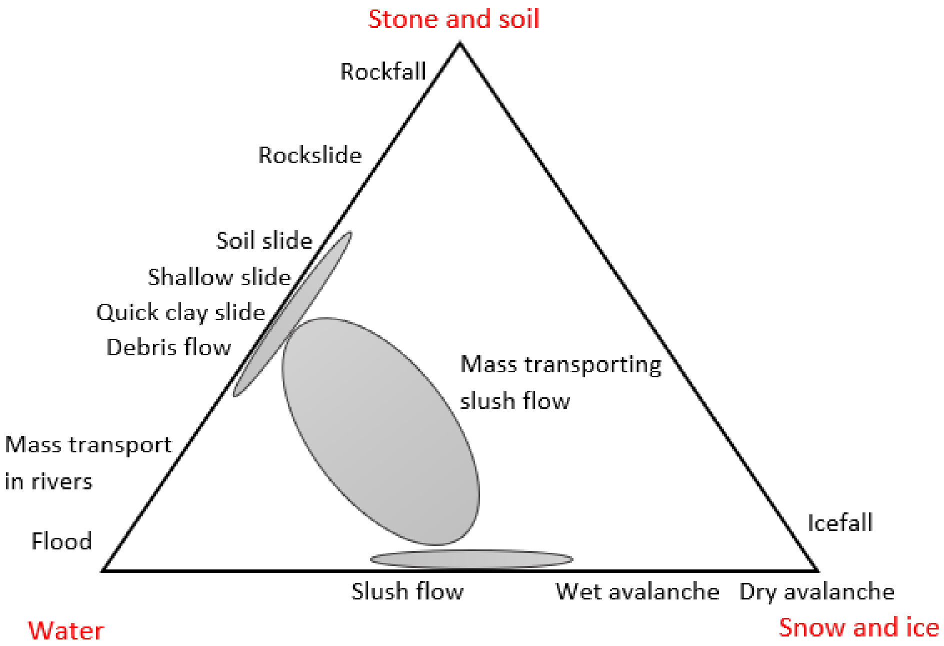


Figure 2.3 Classification of types of slides from the relationship between water, stone and soil, and snow and ice (SVV, 2014a).

When a downstream river is flooding, it can have large discharges that exerts erosional forces on the river banks. If the flood-level reaches the outlet of culvert, this can lead to crushing or blocking of a culvert's outlet construction, causing a reduction in outlet cross-section (Thordarson et al., 2011).

Fluvially transported wood can become lodged in front of the culvert, which will often initiate an accumulation of detritus, sediment and trash, causing the inlet to become blocked. The piece of wood that initiates plugging don't necessarily have to be large; if branches or twigs hits the culvert laterally they only need to be slightly larger than the culvert. This typically occurs for culverts that are smaller than and/or not aligned with the upstream stream and if the inlet is frequently submerged so that wood accumulates in front of the culvert when the headwater retreats (Cafferata et al., 2004). The source of wood is trees along streams or ditches that are exposed to bank erosion, decay and wind- or snow-loads and smaller sticks and branches that are transported with overland flows. Structural measures can be installed to avoid blocking by wood and other larger objects, such as debris deflectors, -nets and -racks. Such structures, however, have to be regularly cleaned to uphold their function (Bradley et al., 2005).

Norway is a country with cold winters, which introduces ice-problems for many culverts. There are two mechanisms that can lead to a culvert being blocked by ice; icing and ice breakup. Icing is the gradual build-up of ice inside the culvert barrel, which occurs if the culvert is exposed to cold air circulation is periods with low discharges (Asvall and Hoseth, 2010). For culverts where icing is a problem one has the option to either reduce the heat losses by covering the inlet and outlet using different insulating measures or to thaw the ice using steaming or heating cables (Bane NOR, 2014b). The ice cover at the bottom of the culvert will also alter the bed roughness (White, 1999). Ice breakup is the fluvial transport of broken-up ice in streams and rivers, which can block the inlet of culverts for stream-crossing and cause a so-called ice jam. The ice can come from developing anchor ice dams that are broken up during winter-periods with larger discharges and rising temperatures or from ice covers that have been loosened from the bank during spring and further broken up by a large and rapid increase in discharge. The first occurs in streams with steeper slopes and the latter with more moderate slopes, and the ice formation requires there to be water in the stream during a long cold-period (Asvall and Hoseth, 2010).

2.2.5 Reduced capacity due to deterioration

Culvert may be deteriorated due to abrasion, corrosion, cracking and deformations. The type and extent of damage depends on the type of material, cover and age of the culvert, and the presence of abrasive sediment-containing water and corrosive materials (Najafi et al., 2008). Culverts don't necessarily have to be old to be deteriorated; problems with joint openings, cracks, misalignment and settlement can occur for relatively new culverts if they are laid on frozen or poorly compressed ground or if their cover is insufficient (Haaland, 2002).

Deterioration will give a reduction in hydraulic capacity since it increases energy losses and may alter the culvert's cross-section. The energy losses are mainly due to a higher roughness. The decrease of hydraulic capacity, however, tends to lag the loss of structural integrity. Measures should consequently be taken before the hydraulic capacity is considerably affected. This supports the current assessment method of culvert deterioration, which is done with respect to structural integrity and not hydraulic capacity (Juliano et al., 2007).

2.3 Effects of climate- and land cover change

Water-driven culvert failure will become altered in the future because of climate- and land cover change. For the culvert failure prediction method to be applicable to evaluate future failure scenarios, these effects must be investigated.

Climate change is the change in frequency of weather conditions, such as average and extreme conditions of temperature and rain. Norway has experienced, and will continue to experience, an increase in mean annual temperature and annual precipitation together with more frequent and intense rainfall events (Hanssen-Bauer et al., 2015). Land cover is the physical and observable cover of an area that can be directly or indirectly changed by human activities. Such changes can result in altered land processes such as hydrology, soil erosion and biodiversity (Ellis, 2013).

This section deals with the relevant effects of climate- and land cover change to the issue of exceedance of culvert capacity. It is divided into the effects on the incoming flood and the effects on the causes behind reduced culvert capacity described in section 2.2, excluding deterioration of culverts.

2.3.1 Effects on the incoming flood

Climate change will give larger and more frequent rain-floods and smaller and fewer snowmelt floods in Norway (Hanssen-Bauer et al., 2015). Projections for floods in Norway by Lawrence and Hisdal (2011) shows that changes in peak flow magnitude and timing varies from region to region, as illustrated in Figure 2.4 and 2.5. The differences reflect the shift from snowmelt- to rainfall-induced peak flows due to increased winter temperatures, which gives less snow storage, and more intense rainfalls. Some regions experience a reduction in peak flow due to smaller snowmelt floods, while the others experience an increase due to larger rain-floods. Change in seasonality occurs mainly for the regions where spring snowmelt is currently dominating. Peak flows will either occur earlier due to earlier snowmelt, or later in the fall or winter due to a shift to rainfall being dominating. A comparison between projections for the mean annual flood and 200-year flood shows that many regions will experience an increase in extreme rainfall larger than that of the general increase, resulting in more extreme low-frequency flood-conditions (Lawrence and Hisdal, 2011).

Climate change will give an increase in short-term extreme precipitation, which affects smaller catchments more than larger ones because of their fast response. This results in larger rain-induced floods for small catchments in all regions (Lawrence and Hisdal, 2011).

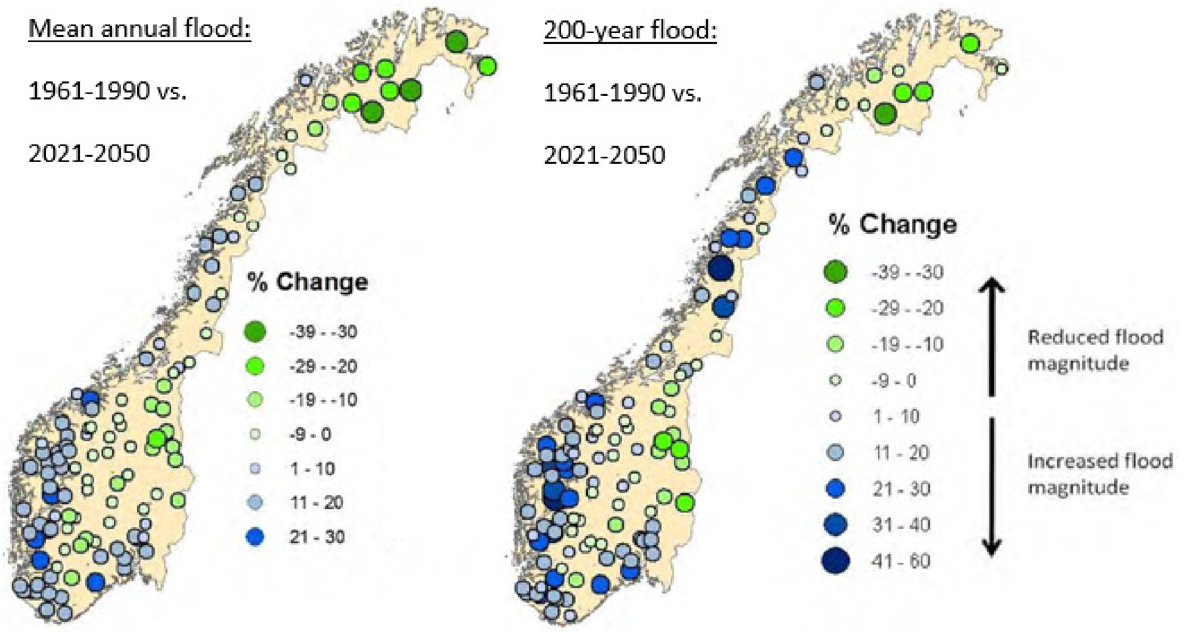


Figure 2.4 Projected percentage of change in the mean annual- and 200-year flood between the 1961-1990 reference period and the 2021-2050 future period– from *Hydrological projections for floods in Norway under a future climate* (Lawrence and Hisdal, 2011).

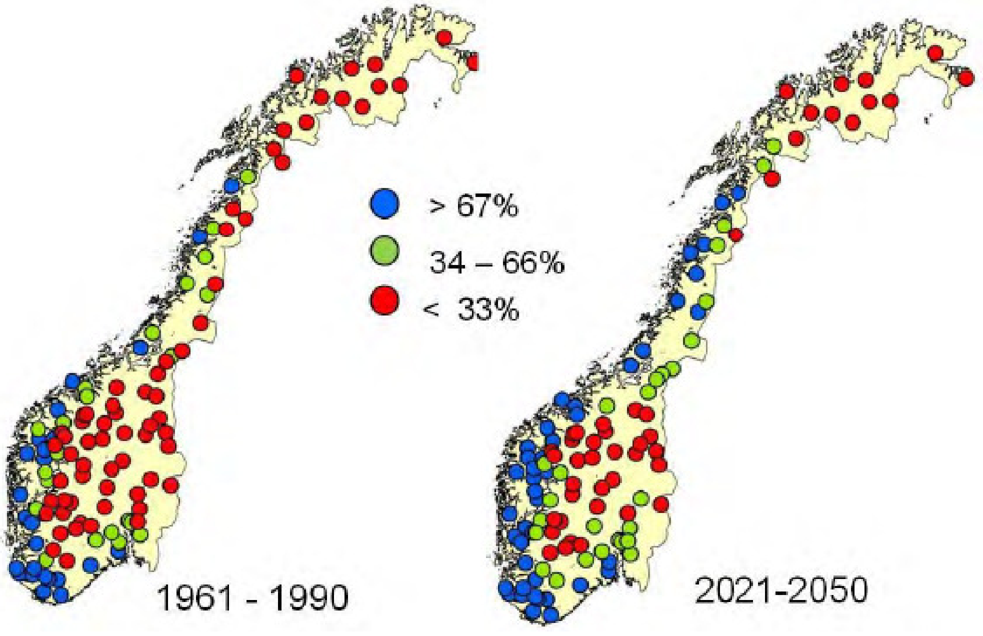


Figure 2.5 Projected change in seasonalityillustrated by percentage of maximum flows occurring during August-February in reference period 1961-1990 and future period 2021-2050 - from *Hydrological projections for floods in Norway under a future climate* (Lawrence and Hisdal, 2011).

Land cover changes due to human intervention, such as urbanization, agriculture and forestry, have a measurable impact on runoff in catchments smaller than 100 km^2 (Kiersch and Tognetti, 2002). It is, however, difficult to ascertain how much land cover changes affects the size and frequency of floods. Deforestation in small catchments will for example lead to increased flows in smaller and medium floods but no significant change in the largest floods. This is because the reduction in infiltration and storage of water that follows deforestation will have little impact when the soil is saturated, which is typically the case in the largest floods (Rinde et al., 2000). Further, the flood response is not only influenced by the presence or absence of forest, but also forestry activities such as drainage, road construction and soil compaction during logging (Calder: cited in Kiersch and Tognetti, 2002). Urbanization and agriculture has the documented effect of increased runoff when they replace forests and will in smaller catchments give larger and faster floods due to reduced permeability and more homogenous surfaces. The establishment of impermeable surfaces in urban areas will especially give higher and more pointed flood peaks (Eikenæs et al., 2000).

2.3.2 Effects on causes behind reduced culvert capacity

Downstream flooding will be affected by climate change and somewhat by land cover change. Climate change will, as talked about in the previous section, give larger floods in some regions and smaller floods in others, giving respectively an increase or reduction in both frequency and magnitude of downstream flooding of rivers (Lawrence and Hisdal, 2011). The effect of land cover change on floods in larger rivers depends on the location, type and extent of the change. Many effects will be lost at larger scales, such as those from local deforestation and urbanization (Eikenæs et al., 2000).

Sediment accumulation can be affected by both climate- and land cover change. Where climate- or land cover change leads to an increase in runoff intensity, frequency and/or duration, there will be an increase in sediment transport in catchments with erodible soils, and a reduction where they lead to the opposite (E Tucker and Slingerland, 1997). Activities that leads to the removal of vegetation and disruption of land surfaces, such as farming and deforestation, will expose erodible soils and followingly give an increase in sediment transport (Eikenæs et al., 2000). If such activities are done in connection to urbanization, a decrease will follow due to establishment of impervious surfaces, and the sediment load will become smaller than it was before (Bradley et al., 2005). Local changes in sediment load will have a measurable impact in basins smaller than 100 km^2 (Kiersch and Tognetti, 2002).

Slides that are initiated by intense or long-lasting rainfall will become more common in Norway due to climate change. This most notably applies for soil slides and debris- and slush flows and to some extent rock slides and -falls. The latter will also be affected by potential fluctuations in temperature that gives more freezing and thawing cycles. Climate change can in some areas reduce the risk of slides due to the rising of forest boundaries as a result of increased temperatures (Hanssen-Bauer et al., 2015). Forests can prevent initiation of slides since they, as mentioned in section 2.2.4, increase the slope stability by increasing soil shear strength and reducing erosion. They can also reduce the outlet length of slides by stopping parts or all of a slide's masses. Deforestation will therefore lead to an increased risk of slides (Høydal et al., 2013).

The amount of floating woody debris can become larger when climate- and land cover change gives larger flows and following increased erosion on vegetated banks. Land cover change and activities connected to it can lead to a change in the source of debris. Deforestation can either give an increase or decrease in the amount of floating debris depending on the logging practice and whether it involves land clearing. Some logging practices will introduce a substantial amount of woody debris to streams and ditches, while others won't. Land clearing will give a decrease in floating debris and is also commonly done in connection to agriculture practices (Bradley et al., 2005).

Ice-related problems in culverts will become altered by climate change due to changes in temperature and flows during winter; the winters will become warmer and winter floods more frequent and larger (Hanssen-Bauer et al., 2015). How the ice-problems are altered largely depends on the existing conditions. Icing can become less common and severe due to less cold-periods during the winter, but the opposite can also occur. Roads and especially railways often lie in the bottom of valleys where temperatures are lower due to inversion, and combined with less insulating snow-cover as a result of climate change this can increase the risk of icing (Trøstaker, 2016). Ice-breaking will become more common in some regions and less in others. The temperature increase combined with larger and more winter floods will make it more common in mountainous- and inland areas, but less common along the coast where winter-temperatures are currently fluctuating between positive and negative. The amount of ice formation will in both cases decrease (Hanssen-Bauer et al., 2015).

2.4 Estimating flood in small ungauged catchments

To be able to estimate the failure occurrence through flood return periods, the culvert failure prediction method must employ a flood estimation method. Eligible methods are therefore investigated in this section.

Catchments connected to culverts will most likely be small and ungauged, meaning that they have areas smaller than about 50 km^2 and no observed time-series of discharge. Flood estimations in such catchments can be done using several methods that can be divided into two main categories; frequency analyses and rainfall-runoff methods. The first uses runoff-series from gauged catchments to estimate the flood and the second estimates the flood by transforming precipitation to runoff (Stenius et al., 2015).

Four flood estimation methods are recommended in *Veileder for flomberegninger i små uregulerte felt* (English: Guideline for flood estimations in small unregulated catchments) (Stenius et al., 2015) published by The Norwegian Water Resources and Energy Directorate (NVE), two under each category:

> Frequency analyses: 1) local frequency analysis – a statistical analysis of flood frequency distribution in observed time-series and 2) the NIFS formulae – a set of equations for estimating flood in small unregulated catchments
>
> Rainfall-runoff methods: 3) PQRUT – a simple one-bucket, lumped hydrological model and 4) the rational method – a linear equation using rainfall intensity and runoff coefficients.

The choice of method depends on available data and catchment size. The guideline generally recommends using the NIFS formulae in ungauged catchments and compare its results with those from other methods. Further recommendations is that the final estimate should be chosen based on an evaluation of accuracy in the results from the different methods with respect to the catchment in question, including whether it should be the weighted average of the results from two or more methods (Stenius et al., 2015).

A short summary of the mentioned methods is given below, divided according to category, followed by a literature study of methods to estimate the effect of climate- and land cover change on floods.

2.4.1 Frequency analysis methods

The result of a frequency analysis is a reference flood value and a growth curve which gives the relationship between the reference flood and a flood with an arbitrary return period. Such analyses are most commonly done on annual peak discharges, but can also be performed on floods over a given threshold or in specific seasons (Stenius et al., 2015).

Local frequency analyses are performed on observed time-series of floods. In ungauged catchments such series does not exist, but it is possible to scale the results from the analysis on a representative gauged catchment. The scaling is based on evaluations of differences in catchment characteristics and how to account for them using catchment parameters (Norem et al., 2016).

The NIFS formula consists of an equation for mean annual flood and an equation for growth curve and is named after the Norwegian government agency program Natural hazards – Infrastructure, Floods and Slides (NIFS) under which it was developed by Glad et al. (2015). The two equations were established by performing a regression analysis on the results from local frequency analyses on annual peak discharges in 165 small gauged catchments in Norway. These equations make it possible to estimate floods in ungauged catchments using only three catchment parameters; area, mean specific runoff in the period 1961-90 and effective lake percentage. The mean specific runoff is extracted from a runoff map developed by NVE (Glad et al., 2015). Estimations will have larger uncertainties for parameters outside those used in the frequency analyses and where the degree of urbanization and/or regulation is substantial. The uncertainty will also increase with increasing return period (Stenius et al., 2015). The interval of parameters used, and general estimations of uncertainty, is given in Table 2.1.

Table 2.1 Parameters and uncertainty in the NIFS formula - interval of parameters are the ones used when developing the regression equations (Stenius et al., 2015).

Parameter	Interval
Area:	0.2 – 53 km^2
Mean specific runoff:	9 – 163 l/s km^2
Effective lake percentage:	0 – 21 %

Return period	Uncertainty
< 100	0.56 – 1.77 times mean flood
> 100	0.5 – 2.0 times T-year flood

2.4.2 Rainfall-runoff methods

Rainfall-runoff methods calculates flood discharges that results from a rainfall event with a specified hyetograph using a hydrological model or formulae. When the flood is a result of only rain, and not snow melt, its size for a given return period can be calculated directly using results from statistical analyses of precipitation. These are most commonly in the form of Intensity Duration Frequency (IDF) curves. IDF curves can be developed at gauging stations with sufficient time-series of precipitation and shows rainfall intensity as a function of duration for different return periods. In such calculations, it is assumed that the rainfall event with a given return period will result in a flood with the same return period. This can be a source of uncertainty since the response of the catchment largely depends on its condition, manly its degree of saturation, when rain falls (Stenius et al., 2015).

PQRUT was developed by Andersen et al. (1983) to be used in flood calculations. Its flood module is a linear one-bucket model with two outlets representing the fast and slow runoff in response to a rainfall event with a specified hyetograph. It requires three parameters for its calculations; two drainage constants for each of the outlets and the threshold value for fast runoff. The model includes developed equations for the three parameters that uses catchment parameters, making it possible to apply the method in ungauged catchments. These parameters are the length, effective lake percentage, mean specific runoff and slope- and height relations found from the hypsographic curve (Andersen et al., 1983). It is recommended to use the model in catchments with sizes of 1-200 km^2 (Holmqvist, 2010). The hyetograph used as input in PQRUT is usually constructed by combining rainfall values with the desired return period that has different durations. It is recommended to lay them symmetrical with the largest values at the center (Stenius et al., 2015).

The rational formula is a method commonly used in very small and/or urban catchments to provide simple flood estimations. Runoff is calculated as a linear function of rainfall intensity using area and a discharge coefficient that expresses how much of the rain goes to runoff. The discharge coefficient depends on land cover and other characteristics of the of the catchment and the intensity of the rainfall (Stenius et al., 2015). Its applicability with respect to largest recommended catchment size varies with different sources; 1 km^2 and 2-5 km^2 is used in the guidelines from Bane NOR and SVV (Bane NOR, 2014a; SVV, 2014c) while 0,2-0,5 km^2 is recommended by Lindholm (cited in Stenius et al., 2015).

2.4.3 Methods for estimating effect of climate- and land cover change

The effect of climate change on floods can be found through establishing emission scenarios and using a series of models to find their associated consequence for floods. Global Climate Models (GCM) are used find large-scale climatic effects which are downscaled to a provide local precipitation and temperature data. The two main methods for downscaling is Empirical-Statistical Downscaling (ESD) and Regional Climate Models (RCM) with postprocessing. The data is then further used as input in hydrological models to provide projections for changes in size and frequency of floods (Hanssen-Bauer et al., 2015).

In climate change adaptation planning it is common to use climate factors in flood estimations instead of the process described above, meaning that the effect of climate change is estimated by multiplying or adding to historical values with a given factor. National and regional factors for both precipitation and floods has been developed based on climate-studies in Norway using the method described above (Hanssen-Bauer et al., 2015). The NVE guideline by Stenius et al. (2015) recommends using climate factors for floods developed by Lawrence and Hisdal (2011) for climate change adaptation, where a minimum of 20% increase is to be considered for all smaller catchments and a 40% increase if they are in certain areas (Hanssen-Bauer et al., 2015).

The effect of land cover change on floods can be simulated using rainfall-runoff methods where land cover parameters can be augmented. This includes several hydrological models and the rational method. The HYDRA-program organized by NVE was established with the purpose to study the effects of human intervention on floods. It resulted in a methodology that uses two hydrological models to simulate the effect of changes; the distributed LANDPINE-model for vegetation changes developed as a part of the program and the semi-distributed SINBAD-model for urbanization developed by SINTEF (cited in Eikenæs et al., 2000). The models require calibration of parameters, which was not performed for smaller catchments in the program (Eikenæs et al., 2000). The NVE guideline by Stenius et al. (2015) provides no recommendations for how to account for land cover changes in flood-estimations.

2.5 Estimating culvert capacity

As the flood return period used to estimate failure occurrence will be based on a comparison between capacity and incoming flood, methods for estimating culvert capacity must be investigated.

Several methods can be used to find culvert capacity that varies both in applicability and complexity. They can in general be divided into theoretical equations solved roughly or by complex computations, and simplified equations and nomograms based on model studies. The latter is the most common method used when designing culverts under roads and railways, where equations are usually applied in the cases where nomograms don't exist. In some difficult cases, however, one may need to solve complex computations using computer software (Norem et al., 2016). An example of such software is HEC-RAS, which is an analysis tool for computing water surface profiles on stream reaches (Schall et al., 2012).

This section looks first into common culvert designs and culvert hydraulics in general. A literature study of some capacity calculation methods for relevant flow situations is then performed, including for blocked culvert capacity.

2.5.1 Common culvert designs

There exist numerous designs for culverts, and the dimensions, shape and material are chosen dependently and with consideration of other parameters such as earth pressure and abrasion- and corrosion danger. The most common shapes for culverts are box and circular, where box culverts are used for larger dimensions and pipe culverts for smaller. Pipe culverts are typically made of corrugated metal, concrete and plastic, while box culverts are mostly of concrete with the exception of some older ones of masonry (Jenssen, 1998). The old masonry culverts can have problems with stones shifting and falling out and is therefore commonly wholly or partly lined with other materials (Bane NOR, 2014b).

Culverts commonly either projects out of the embarkment or is flush with the embarkment slope or with a headwall or wingwall. Circular pipe culverts can be built with all three types of configurations, while box culverts are never projected (Norem et al., 2016).

2.5.2 Culvert hydraulics

There can be several flow situations in a culvert. It is typical to divide them into two categories with respect to hydraulic control; inlet control and outlet control. The type of control reflects the location of critical flow and followingly what limits the hydraulic capacity of the culvert. The situations can further be divided into six main types, two for inlet control and four for outlet control. Additional two types can be added when accounting for overtopping weir flow (Norem et al., 2016). These are illustrated in Figure 2.6 with a dotted line representing the critical depth to show where critical section occurs. This where the water uses the least amount of specific energy, which is water depth plus velocity head, to convey the water. In this section, the Froude number is 1, and it represents a transition between subcritical flow to supercritical flow (Tesaker, 2010).

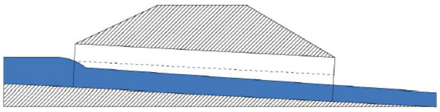
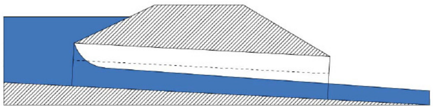
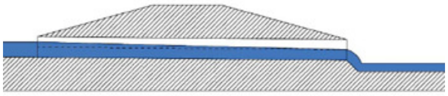
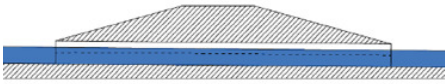
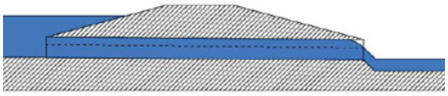
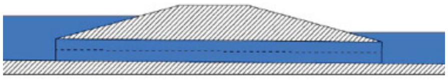
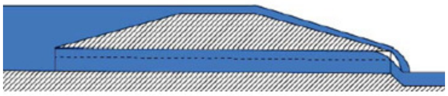
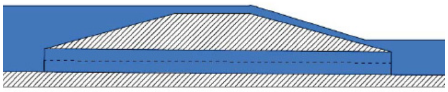
	**Inlet control** with unsubmerged weir flow at the inlet and supercritical flow in the barrel.
	**Inlet control** with orifice flow at the inlet and supercritical flow in the barrel.
	**Outlet control** with subcritical flow and critical section at outlet.
	**Outlet control** with subcritical flow and critical section downstream outlet.
	**Outlet control** with pressurized flow and critical section at outlet.
	**Outlet control** with pressurized flow and critical section downstream outlet.
	**Outlet control and overtopping** weir flow with pressurized flow and critical section at outlet.
	**Outlet control and overtopping** weir flow with pressurized flow and critical section downstream outlet.

Figure 2.6 Flow situations at culverts including overtopping – from *Overvannshåndtering og drenering av veg og jernbane* (English: Stormwater management and drainage of road and railways) (Norem et al., 2016).

The type of control and flow situation that occurs depends on the amount of incoming water, upstream and downstream water level and the design and condition of the culvert. Inlet control occurs when the inlet is less effective than the barrel at conveying the water, resulting in critical flow occurring in the inlet-zone. Outlet control occurs when the barrel is less effective than the inlet to convey the water or if downstream water levels are too high, resulting in critical flow occurring at or downstream of the culvert outlet. The first gives a capacity that is only decided by upstream energy level and inlet size and -design, while for the latter it is decided by energy losses though the whole culvert and upstream and downstream energy levels (Norem et al., 2016).

The headwater level that gives submersion of the inlet depends on the type of hydraulic control and inlet design. For outlet control, it will occur when the headwater is at the same level as the top of the culvert, while for inlet control it can rise further due to the weir flow. The transition from unsubmerged weir flow to submerged orifice flow depends on the inlet design, but it often approximated to occur for headwater levels 1.2 times the culver height (Norem et al., 2016).

It’s the upstream water energy that “drives” the water through the culvert, which consists of potential energy and kinematic energy represented by the specific energy. For a given upstream specific energy level, the culvert will have a certain capacity, and their relationship is shown with a performance curve as illustrated in Figure 2.7. It’s the limiting type of flow that will occur for a certain situation, meaning the one that gives the least capacity for a given upstream water level (Norem et al., 2016). In culvert analyses it is often assumed that the water has no velocity in the channels upstream or downstream the culvert, so that performance curves typically shows headwater level as the only contribution to upstream water energy. This is a conservative assumption, since it overestimates entrance and exit energy losses and thereby gives a smaller capacity (Schall et al., 2012).

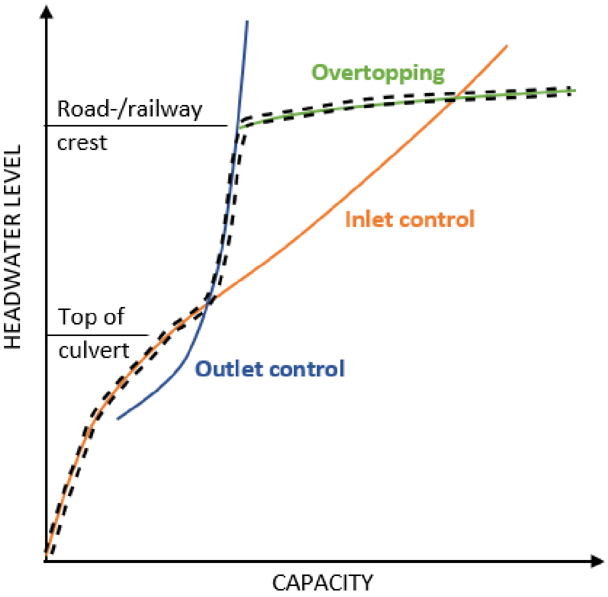


Figure 2.7 Typical performance curve for culverts where the dotted line shows the overall performance.

2.5.3 Methods for inlet-controlled flow

With unsubmerged inlet control, we will have open channel flow where the culvert entrance works as a weir that forces the water into critical flow. With submerged inlet control, the culvert entrance works as a orifice opening, where the water flows freely on the downstream side of the entrance (Schall et al., 2012). The relationship between discharge and headwater level in these two situations can in theory be determined by using the Froude number equation at the critical section in combination with Bernoulli's energy equation. Under ideal conditions with no energy losses or disrupted flow- or pressure conditions and no velocity in the headwater, the capacity can then be calculated by only defining headwater level and inlet dimensions. The flow conditions at the entrance is in reality very complex. Weir- and orifice equations in various forms is therefore used, which applies coefficients that differs from various types of constructions (Tesaker, 2010).

Equations for inlet-controlled discharge- and headwater calculations has also been developed specifically for culverts. Culvert discharge equations presented in *Open channel hydraulics* by French (1987) are similar to the traditional weir- and orifice flow equations in the usage of discharge coefficients. The discharge coefficient is found and adjusted according to the inlet configuration and type of flow using equations, graphs and tables. For unsubmerged flow, the process of adjusting the discharge coefficient is interchangeable with finding critical depth and discharge. For submerged flow, adjustments are not needed, and the discharge coefficient can be directly read from tables according to inlet configuration and submergence ratio. Inlet control equations has also been developed by the Federal Highway Administration (FHWA) based on model studies. In *Hydraulic design of highway culverts* by Schall et al. (2012), three of these equations are presented; two for unsubmerged flow and one for submerged. The three equations are quite similar and relies on the use of constants that can be directly read from tables according to culvert configuration. Several nomograms have been developed based on these equations, which shows the relationship between headwater level, diameter and capacity for a given inlet configuration and flow situation (Schall et al., 2012).

2.5.4 Methods for full barrel flow

Pressurized flow for outlet-controlled culverts will occur when the headwater exceeds the top of the culvert. When the outlet is submerged the entire barrel will have pressurized flow, giving a situation often referred to as full barrel flow. With an unsubmerged outlet the outlet section of the culvert may have free-surface flow. With full barrel flow, Bernoulli's principle together with equations for energy losses in pressurized pipes can be applied to find the relationship between discharge and headwater. In the case of free-surface flow at the outlet section, more complex water-surface profile computations have to be performed, typically using computer software (Tesaker and Hoseth, 2010). Methods for this situation is not further investigated.

The most common methods for calculating full barrel flow in culverts involves the method of energy balance described above. This methodology is directly applied in *Hydraulic design of highway culverts* (Schall et al., 2012) , where entrance-, friction- and exit loss is always considered in addition to other relevant losses at for example bends, junctions and grates. The equations used for singular losses are a function of velocity head, and friction loss is calculated using either the Manning or Darcy equation where Manning is most commonly used for culverts. Manning's n values and entrance loss coefficients are also given for several designs and materials. Another type of methodology is applied in *Open channel hydraulics* (French, 1987), which is similar to the one for inlet-controlled flow in the usage of discharge coefficients found and adjusted with tables and graphs. Entrance- and exit losses are not separately considered, and a different form of Manning's formula is applied.

2.5.5 Methods for calculating blocked culvert capacity

Calculations of capacity in blocked culverts are generally not done when designing culverts and little literature exists to guide such a procedure without complex computations. The FHWA recommends modifying barrel parameters, such as increased entrance loss coefficients, additional roughness or reduced barrel area, when calculating blocked capacity. It is, however, also recommended for such analyses to be performed with computer software and no further guidance is given (Bradley et al., 2005).

In the NIFS report *Overvannshåndtering og drenering av veg og jernbane* (English: Stormwater management and drainage of road and railways) by Norem et al. (2016), it is recommended to account for blockage in outlet-controlled culverts by increasing the entrance loss coefficient. Entrance loss coefficients for blocked inlets are given for circular and box culverts and the main types of inlet configurations. These coefficients originate from *Hydraulic loss coefficients for culverts* (Tullis, 2012), a report developed as a part of the National Cooperative Highway Research Program (NCHRP). This report consists of result from model tests on embedded/open-bottom culverts, specifically circular culverts with invert burial of 20%, 40% and 50% and elliptical culverts with 50% burial. The difference in the entrance loss coefficients varied little with invert burial percentage and, consequently, a single representative value is recommended to be used for all burial percentages. Such values are given for the main inlet configurations in the NCHRP report (Tullis, 2012). Entrance loss coefficients were not developed for box culverts in this work, but Norem et al. (2016) has derived conservative values based on the NCHRP report's results for mitered circular inlets, which is argued to have flow-conditions similar to rectangular inlets.

Other results from *Hydraulic loss coefficients for culverts* (Tullis, 2012) includes regression constants for embedded culverts used in the three equations for inlet-controlled flow developed by FHWA, where different constants are given for the tested burial percentages. Methods for handling composite roughness in embedded/open-bottom culverts were also tested, and it was found that the traditional mean velocity assumption method developed by Horton to calculate composite Manning's n value provided reasonably accurate results (Tullis, 2012).

Manning's n values for natural channels with gravels and cobbles is given in the FHWA report by Schall et al. (2012) and many other literature sources. Manning's n values for ice-covered surfaces exists to a smaller degree, and the only values found is for roughness beneath ice covers. The report *Hydraulic and physical properties affecting ice jams* by White (1999) developed as a part of the Cold Regions Research and Engineering Program Work (CRREL) presents recommendations for ice cover roughness based on data from multiple studies.

2.6 Culvert-related databases and tools

For the culvert failure prediction method to be feasible as a desktop study, it should reflect the quantity and quality of data that is available. The following is a short review of public Norwegian databases and tools that contain relevant culvert configuration- and catchment data.

Culvert configuration data is information about culvert geometry, dimensions, design and so on. Such data exists in the databases of The Norwegian Public Road Administration (SVV) and Bane NOR along with other data on objects in the road- and railway infrastructure. They are called National Road Database (Norwegian: Nasjonal vegdatabank, NVDB) and BaneData, and publicly available data from these databases can be found in the web map services Vegkart and Banekart.

An initial review of these databanks shows that there is little consistency with the digitization of data, and that the amount of registered data strongly varies. The feature data that most commonly appears is given Table 2.2 along with the number of culvert objects where the feature is registered and the belonging percentage with respect to the total number of registrations. Note that this is done through a quick overview using the web map services and may not display completely accurate information.

Catchment data is information about the characteristics of the catchment, both hydrological and geological, and data relevant to floods and slides. The web map service NVE Atlas presents a large amount of these data, including records and danger- and caution maps of floods and slides. NVE has also developed a catchment-generation web service called NVE Nevina, which estimates catchment parameters and indexes for the catchment belonging to a given point that can be used for flood estimations. The service requires the point to be placed on or near a defined river network, so it can have trouble generating very small catchments that are not on the network.

Table 2.2 Overview of culvert features registered in the databanks NVDB and BaneData showing the number of objects and the corresponding percentage with a given feature.

Total no. of culvert objects:	532840		16377	
Feature	**NVDB**		**BaneData**	
	no.	%	no.	%
Material type[1]	464574	87	15325	94
Cross-sectional shape[2]	393957	74	10993	67
Diameter / width and height	446431	84	13865	85
Type of inlet[3]	154194	29	511	3
Length	400987	75	3018	18
Slope	221	0	3018	18
Cover height	46482	9	9594	59

[1] Material type: concrete, steel, plastic, stone

[2] Cross-sectional shape: circular, rectangular, arch, elliptical

[3] Type of inlet in NVDB: open in ditch or with headwall

[3] Type of inlet in BaneData: headwall, mitered, projecting

3 Material and method

The purpose of this work is to answer a series of scientific questions in a case study of culvert failure in Soknedal. The culvert failure prediction method is the tool to answer these questions, which is developed in this chapter using the investigated theory and literature. The method is developed with aim of practicality and feasibility as a desktop study in risk assessments in addition to being able to fulfill the purpose of answering the scientific questions.

Fault tree analysis is used as risk methodology in the culvert failure prediction method. The evaluation behind this choice in addition to how the analysis is applied to culvert failure is first presented. Based on this, the method for prediction is established followed by a description of how it is encoded into an Excel workbook. The workbook is tested to make sure that it will provide reasonable results in the case study. The case study is then presented and prepared, where data is collected and evaluated, and three analyses that uses the workbook to answer the scientific questions are established.

3.1 Risk methodology behind prediction

The scientific questions largely deal with finding the occurrence interval of culvert failure, which reflects the technical risk perspective used in risk management within Infrastructure Asset Management (IAM) or risk- and vulnerability (ROS) analyses as described in section 2.1.1. Such a perspective calls for culvert failure and its causes being clearly defined and that the effect of the causes on failure occurrence can be modelled.

The fault tree method is chosen as the risk methodology since it is well-known and provides an analytical approach to finding causes of culvert failure that can be used to give quantitative results for risk estimations. The framework developed by Kalnes (2017) is further applied by continuing to use its definition of culvert failure on two levels and the technical specification of exceedance of critical capacity. Such a definition makes it possible to find the occurrence of culvert failure though the return period of exceeding flood and it somewhat defines the potential consequences of culvert failure through using requirements to headwater level.

The assessment methods used by SVV and Bane NOR are similar to the one used in the framework by Kalnes (2017) in the sense of comparing capacity and flood size. The comparison is, however, only between design culvert capacity and dimensioning flood and the culvert's condition is only considered through qualitative assessments. Other flooding situations than the dimensioning is not explored, so that occurrence of flooding is only assessed in terms of more or less than what is accepted. Since only design capacity is considered, the only measure whose effect can be modelled with respect to increasing capacity is replacement of the culvert. The methods thus provide little quantitative results that can be used to answer the scientific questions and in risk management, which further supports the choice of using Kalnes' (2017) approach with fault tree analysis.

3.1.1 Definition of culvert failure

The definition of culvert failure by Kalnes (2017) is kept due to its reflection of a technical risk perspective and because its technical specification provides a way to estimate failure occurrence that accounts for most of the water-related culvert risks described in section 2.1.2. Except for formation of scouring holes due to large outlet velocities and piping due to water seeping in and out of cracks, all the risk deals with a rising of the headwater above certain levels. The two levels of failure provide a differentiation of the potential consequences of failure; the various risks that deals with water standing in front of the embarkment is covered in the flood-situation, and in the extreme-situation these risks are increased in addition to introducing overtopping of the road/railway.

The only alteration of the definition is to the headwater level that gives critical capacity in the flood situation. For inlet-controlled culverts, the headwater can rise above the top of the culvert before the inlet is submerged (see section 2.5.2). The same headwater level will therefore not cause the water to take alternative paths and stand in front of the embarkment for inlet- and outlet-controlled culverts. Under the assumption provided by Norem et al. (2016) that inlet-controlled culverts become submerged at headwater levels 1.2 times the culvert height, the headwater at critical capacity is increased to this level for inlet-controlled culverts to account for their residual capacity.

Table 3.1 Definition of culvert failure with technical specification in a general context and at the two levels of planning.

Definition	Technical specification
Culvert is not able to safely lead away water.	Critical capacity ($Q_{cap,crit}$) is exceeded.

Level of planning	Additional definition	Headwater level at critical capacity
Flood-situation	Water takes alternative paths.	Inlet control: 1,2 times height ($1.2H$) Outlet control: Top of culvert (H)
Extreme-situation	Water takes unwanted alternative paths.	Top of road/railway (R)

3.1.2 Construction of fault tree for culvert failure

The fault tree by Kalnes (2017) is constructed to give the critical capacity for which a flood with a given return period can be compared to, and the framework can be used to predict failure occurrence by testing several flood-sizes. The omittance of the flood-element in the fault tree is somewhat flawed, since the failure definition refers to the event of exceedance of critical capacity which is an event that occurs in response to a flood. The fault tree should therefore include the flood-element, both to better reflect the failure definition and to avoid having to test several flood-sizes to find the occurrence of failure.

Such an alteration calls for a separate construction of a fault tree instead of directly applying the one developed by Kalnes (2017). This is also to include elements uncovered in the investigation of exceedance of culvert capacity in section 2.2 that is not included in Kalnes' fault tree. As the *Fault Tree Handbook NUREG-0492* (Vesely et al., 1981) is one of the best sources for performing fault tree analyses, the directions and recommendation from this handbook is used to construct the fault tree for culvert failure:

A fault tree consists of four basic elements: 1) The top event, which defines the system failure. 2) Primary events; basic-, conditioning-, undeveloped- and external events, which don't need to be further developed, 3) Intermediate events, who occur because of one or more causes that are linked through logic gates. 4) Logic gates, which links one or more input events to an output event. The OR-gate specify that the output event will occur if any of the input events occur, meaning they are specifications of the output event since causality never passes through OR-gates. The AND-gate specify that the output event will only occur if all the input events occur, meaning they collectively cause the output event. The comprehensiveness of the fault tree is defined by establishing system boundaries. The external boundary is given by the definition of failure. The internal boundary is the limit of resolution used determined by the level of detail of the primary events which should reflect the quantity and quality of available data. This is both to be able to give results and to avoid a false sense of accuracy. The concept of failure effects, -modes and -mechanisms is central in the fault tree construction. Failure effects deals with the effect the failure, failure modes define why the effect occurs, and failure mechanisms gives how the mode can occur. Basic events are failure mechanisms that can also be a failure modes (Vesely et al., 1981).

Using the concepts described above, the fault tree is deductively constructed. The top event of culvert failure has a definition that in itself presents the two events that cause it; the culvert has a critical capacity which occurs simultaneously as a flood larger than this capacity, and the two are intermediate events linked with an AND-gate. A flood from the culvert's catchment or a neighboring catchment are basic events in the form of both failure mechanism and -mode that linked with an OR-gate can give the effect of a flood larger than the capacity. The critical capacity is decided by the condition of the culvert and is initially divided into the culvert having design capacity or reduced capacity. The first is a basic event in itself and therefore both mechanism, mode and effect while the latter is an effect of multiple modes and their mechanisms. Downstream flooding, deterioration and blocking are all modes that connected with an OR-gate will give the effect of a reduced capacity. Downstream flooding and deterioration are both modes and mechanisms that are not further developed. Blocking is divided into three sub-modes connected with an OR-gate to separate the mechanisms according to which what part of the culvert they will give blocking in; inlet, outlet or barrel. Mechanisms behind blocking of culvert inlet is sediment accumulation at inlet, upstream slide, embarkment slide at inlet, wood lodging and ice breakup. Upstream slide is further specified according to the type of slide using an OR-gate; snow, soil or rock. Mechanisms behind blocking of culvert outlet is erosion by downstream river and embarkment slide at outlet. Mechanisms behind blocking of culvert barrel is sediment accumulation in barrel and icing, which will give an altered roughness in addition to the reduction in cross-sectional area. All the mechanisms are connected with OR-gates to their respective sub-mode. Note that some of the mechanisms under different sub-modes are similar which is a result of them not being extensively developed.

The most common way to display the fault tree is through a diagram. Figure 3.1 is a diagram that displays the fault tree described above. The symbols used in the diagram represents the following elements of the fault tree:

Basic event: circle

Intermediate events: rectangle

OR-gate: shield with curved base

AND-gate: shield with flat base

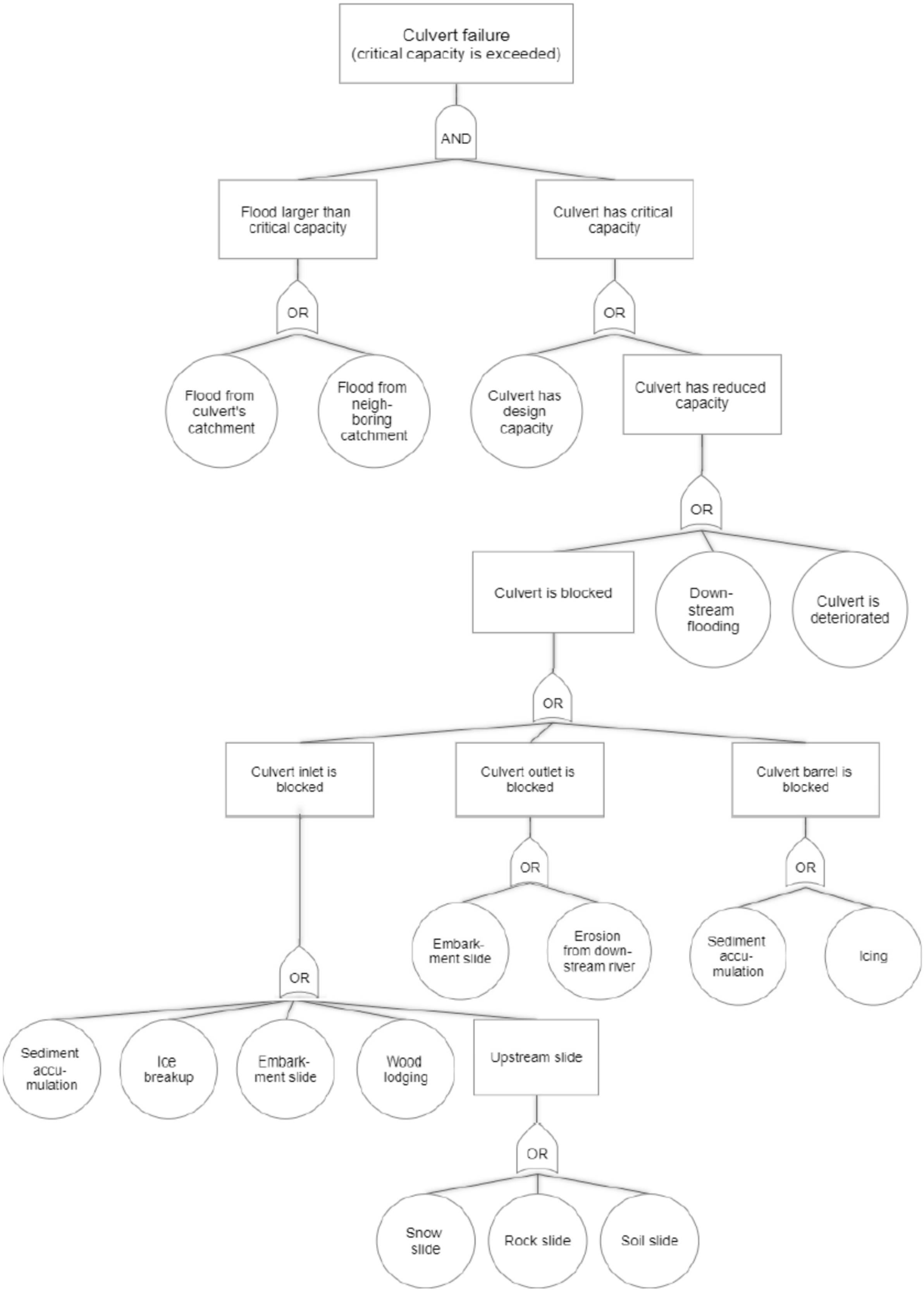


Figure 3.1 Fault tree diagram for culvert failure displaying the logic of the constructed fault tree. Diagram is made with the online trail copy of SmartDraw.

3.2 The culvert failure prediction method

The culvert failure prediction method is developed in this section using a selection of the different methods described in the theory and literature study, chosen with respect to the aim and purpose of the method. The level of complexity used is low, which reflects the aim of practicality, the available data and that the time constraints of the work only allows simple considerations of the many factors that are involved in the prediction.

The culvert failure prediction method can be divided into three elements; application of fault tree for culvert failure, calculation of culvert capacity and calculation of flood return period.

3.2.1 Application of fault tree for culvert failure

The applied fault tree consists of modes and mechanisms whose effect can be modelled using simple methods. The two failure modes of deterioration and blockage of culvert outlet is therefore omitted in the applied fault tree because the literature study could not uncover how to model their effect on capacity using such methods. The choice of emitting deterioration is also expedient as it is an issue that falls under assessment of structural integrity rather than culvert capacity, as described in section 2.2.5.

All the failure modes in the fault tree is treated as known inputs except for the flood from the culver's catchment whose return period gives the occurrence interval of failure. This makes the application of the fault tree somewhat unconventional, where one can divide between a qualitative and quantitative application of the fault tree.

The qualitative application of the fault tree is the evaluation of failure mechanisms. This application is used in investigation of recorded cases of culvert failure to uncover the causes of failure and in exploration of possible future cases of culvert failure to determine inputs for failure modes and the validity of failure occurrence estimations. In the exploration, it is important to consider the temporal aspect of the failure mechanisms and not only whether they can or cannot occur. This includes evaluating whether failure mechanisms can occur simultaneously as the exceeding flood and if the failure occurrence from flood return period is over- or under estimated with respect to the occurrence of other failure mechanisms.

The quantitative application of the fault tree is finding failure occurrence by comparing flood and critical capacity with the given inputs for failure modes. Failure mechanisms are not included in this application unless they are also failure modes. To determine the capacity, the following inputs for the modes that leads to a reduced capacity is given; percentage of height blocked at the inlet, percentage of height blocked in the barrel and bed material and downstream water level as percentage of height. Blocking of barrel gives an equal blocking of inlet if the latter is smaller than the former. If the inputs specify no reduction in capacity, the culvert will have a design capacity. The size of the flood from a neighboring catchment which is conveyed to the culvert through alternative floodways is given as an input in m^3/s. In the extreme situation, the water can go into alternative floodways before overtopping occurs. This is not included in the fault tree but is added as an additional input when studying culvert failure in the extreme-situation by giving the capacity of the alternative floodway in m^3/s.

Table 3.2 Inputs used in the quantitative application of fault tree for culvert failure that are determined through the qualitative application and evaluation of contributions from alternative floodways.

Input	Given as
Blocked inlet	% of height
Blocked barrel	% of height
	Bed material (sediments or ice)
Downstream flooding level	% of height
Incoming discharge from alt. floodway	m^3/s
Outgoing discharge to. alt. floodway	m^3/s

3.2.2 Calculation of culvert capacity

The failure definition and modelled modes of failure gives the four types of flow situations that should be modelled; submerged and unsubmerged inlet-controlled flow and pressurized outlet-controlled with submerged and unsubmerged outlet. Since outlet-control with unsubmerged outlets where free-surface flow can occur requires complex calculations, it is assumed that the culvert is inlet-controlled unless downstream flooding is specified as an occurring failure mode. In this case, full barrel flow is modelled and compared to the capacity found with inlet control. All the failure modes must be considered for full barrel flow, while only blocking of inlet must be considered for inlet-controlled flow.

The literature study in section 2.5 shows that there are several methods that can be used to determine capacity in the three flow situations. The choice of method is based on an aim of practicality; it should be applicable under different types of failure modes and without having to extensively specify the culvert configuration. It is, however, important to note that the choice is also largely based on subjective evaluations. To limit the extensiveness of the calculation, only a selected number of culvert configurations are considered, shown in Table 3.3.

Table 3.3 Culvert configurations considered in capacity calculations.

Cross sectional shape	Circular
	Rectangular
Entrance type	Headwall with square edge
Longitudinal shape	Straight and uniform
Material type	Smooth
	Rough

Inlet-controlled weir flow is modelled using the Froude number equation at the critical section in combination with Bernoulli's energy equation under the assumption of no energy losses between the headwater and the critical section and no velocity in the headwater. This is referred to as the simplified Froude method from this point. The reason behind this choice is that the culvert-equations for weir flow described by French (1987) and Schall et al. (2012) are deemed too dependent on the specification of culvert configuration and followingly requires substantial amounts of input in addition to not being generally applicable for blocked culverts. Further, it is assumed that the simplified Froude method will give reasonably accurate results since the two assumptions will somewhat balance each other out; one underestimate losses and the other overestimates. The simplified Froude method consists of the usage of three equations. Eq. (1) and (2) are established using the relationship between velocity and discharge ($U = \frac{Q}{A}$), the Froude number at critical section ($Fr_c = \frac{U_c}{\sqrt{g y_{h,c}}} = 1$) and energy balance with no energy losses and no headwater velocity ($y_{HW} = y_c + \frac{U_c^2}{2g}$). Eq. (3) is the hydraulic depth at critical section (French, 1987). Eq. (2) and (3) are used either through their direct relationship or by iteration to determine the hydraulic depth used in eq. (1) to find culvert capacity.

$$Q = A_c \sqrt{g y_{h,c}} \tag{1}$$

$$y_{h,c} = 2\,(y_{HW,o} - y_c) \tag{2}$$

$$y_{h,c} = \frac{A_c}{Tc} \tag{3}$$

where

Q = Culvert discharge capacity [m^3/s]

A_c = Flow area at critical section [m^2]

g = Gravitational acceleration [9.81 m/s^2]

$y_{h,c}$ = Hydraulic depth at critical section [m]

$y_{HW,o}$ = Headwater depth referenced to open inlet (see Figure 3.2) [m]

y_c = Water depth at critical section [m]

Tc = Width of free water surface at critical section [m]

It is important to note that the headwater level used in eq. (2) is referenced to the open inlet height, which will decrease when the culvert is blocked as illustrated in Figure 3.2. This also applies for the assumption of when the transition to orifice flow occurs; the inlet becomes submerged when the headwater level is 1.2 times the *open* culvert height.

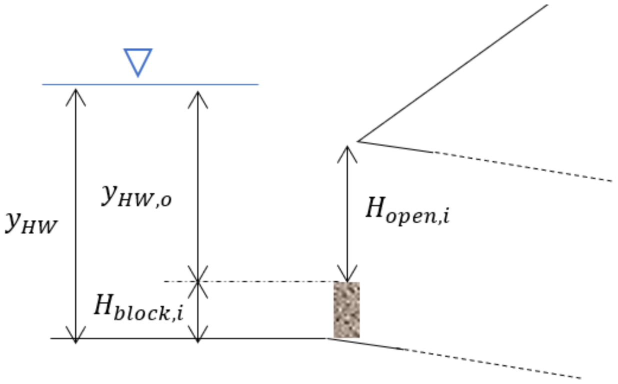


Figure 3.2 Definitions of headwater depths and open and blocked inlet height.

Inlet-controlled orifice flow is modelled using the culvert-equation for orifice flow described by French (1987) under the assumption that the discharge coefficients for square edge headwall can be applied for all culvert configurations and under blocked conditions. This is referred to as the orifice equation method from this point. The reason behind this choice is that the simplified Froude method will likely grossly underestimate entrance losses in this flow situation, and the culvert-equation for orifice flow by FHWA described by Schall et al. (2012) is deemed more depended on the specification of culvert configuration than the one provided by French (1987). The discharge coefficients for a square edge headwall provides a somewhat intermediate estimate of capacity with respect to other inlet configurations; flared ends or more rounded edges gives higher coefficients, projecting or flush inlets gives lower coefficients and wingwalls can give higher or lower depending on its angle. Culvert capacity is calculated using eq. (4) and interpolating discharge coefficients from Table 3.4 (French, 1987):

$$Q = C_D A_i \sqrt{2gy_{HW,o}} \tag{4}$$

where

C_D = Discharge coefficient [-]
A_i = Cross-sectional area of inlet [m^2]

Table 3.4 Discharge coefficients for square edge headwall where $H_{open,i}$ is the open inlet height (Bohaine cited in French, 1987).

$y_{HW,o}/H_{open,i}$	C_D
1.4	0.44
1.5	0.46
1.6	0.47
1.7	0.48
1.8	0.49
1.9	0.5
2.0	0.51
2.5	0.54
3.0	0.55
3.5	0.57
4.0	0.58
5.0	0.59

Full barrel flow is modelled using Bernoulli's energy equation together with equations for energy losses, referred to as the energy balance method from this point. Note that this is can only model downstream flood levels that are at the same or higher level than the culvert outlet roof. The equation described by French (1987) is chosen away mainly due to it being more complex and generally less used. Since only a straight and uniform barrel is considered, the energy losses that are calculated is entrance-, friction- and exit losses and other losses that occur are assumed negligible. It is further assumed that the headwater and tailwater has no velocity. The discharge is found using eq. (5), which is established from using the formulas for entrance- and exit loss as a function of velocity head ($H_e = k_e \frac{U^2}{2g}$ and $H_O = \frac{U^2}{2g}$) and the Manning's formula for friction loss ($H_f = \frac{2gLn^2}{R^{4/3}} \frac{U^2}{2g}$) together with energy balance between headwater and tailwater and the above assumptions. Eq. (6) defines the height difference between the headwater and tailwater (Schall et al., 2012).

$$Q = A_b \sqrt{\frac{2g\,\Delta y}{1 + k_e + \frac{2gLn^2}{R^{4/3}}}} \tag{5}$$

$$\Delta y = y_{HW} + SL - y_{TW} \tag{6}$$

where

A_b = Cross-sectional area of barrel [m^2]
Δy = Height difference between headwater- and tailwater level [m]
k_e = Entrance loss coefficient [-]
L = Length of culvert [m]
n = Manning's roughness coefficient [$s/m^{1/3}$]
R = Hydraulic radius of full flowing barrel [m]
y_{HW} = Headwater level referenced to bottom of culvert inlet [m]
S = Slope of culvert [m/m]
y_{TW} = Tailwater level referenced to bottom of culvert outlet (given by downstream flood level) [m]

The entrance loss coefficient is dependent on inlet configuration and, as with discharge coefficient for orifice flow, a square edged headwall provides an intermediate value with respect to other configurations. It is therefore assumed that it provides a representative value. Blocking will increase the entrance loss coefficients, and following the recommendation in the NCHRP report (Tullis, 2012) a single value is used for all burial percentages. Entrance loss coefficients used in calculations is given in Table 3.5.

Table 3.5 Entrance loss coefficients for square edged headwall for open culverts (Schall et al., 2012), blocked pipe culverts (Tullis, 2012) and blocked box culverts (Norem et al., 2016).

	Open culvert	Blocked culvert
Box culverts	0.5	0.65
Pipe culverts	0.5	0.55

Manning's roughness coefficients are given in several sources and its specification according to material, age, shape and size of the culvert can be extensive. Such information will not be provided, and it is therefore expedient to use typical values to not give a false sense of accuracy. Typical values for rough and smooth materials provided by Schall et al. (2012) is used, shown in Table 3.6. With respect to the most common culvert materials, the smooth Manning's number is assumed to apply for culverts in concrete and plastic and the rough for culverts in corrugated metal and masonry.

Table 3.6 Manning's n values for rough and smooth culvert materials and bed material of sediments (Schall et al., 2012) and ice (White, 1999).

	Material	Manning's n value
Culvert	Smooth (concrete, plastic)	0.012
	Rough (corrugated metal, masonry)	0.024
Bed (blocking)	Sediments (gravel and cobbles)	0.040
	Ice (smooth ice cover)	0.010

Altered bed roughness for a blocked barrel is modelled by using a composite roughness in the discharge eq. (5). The Manning's n value used for the bed-materials is given in Table 3.6. They originate from studies of natural streams, and therefore the lower range value provided by Schall et al. (2012) for gravel and rubble and by White (1999) for ice covers is used as it is assumed that the roughness will be somewhat lower than what will occur naturally in streams. The composite roughness is found using the mean velocity assumption method developed by Horton (Tullis, 2012):

$$n_c = \left(\frac{P_{culv} n_{culv}^{3/2} + P_{bed} n_{bed}^{3/2}}{P} \right)^{2/3} \tag{7}$$

where

n_c = Composite Manning's n value [s/m$^{1/3}$]
P = Total wet perimeter [m]
P_{culv} = Wet perimeter of culvert material [m]
n_{culv} = Manning's n value of culvert material (smooth or rough) [s/m$^{1/3}$]
P_{bed} = Wet perimeter of bed material [m]
n_{bed} = Manning's n number of bed material (sediments or ice) [m$^{1/3}$/s]

Several geometric parameters are presented in these methods; flow-, inlet- and barrel area, open height, hydraulic width, hydraulic radius and wetted perimeter. Their equations as a function of degree of blocking together with illustrations for box and pipe culverts are given in Appendix A.

3.2.3 Calculation of flood return period

The flood return period is found through performing backwards flood-calculations. The literature study in section 2.4 shows that there are four flood estimation methods used in Norway for small ungauged catchments; local frequency analysis, the NIFS formulae, PQRUT and the rational method.

The NIFS formula is used as the only method, mainly due to it being the one with least requirements to input data. Only three catchment parameters are required and there is no need to evaluate data from gauging stations, making it possible to perform calculations without extensive hydrological knowledge. Local frequency analysis is chosen away solely due to the extensive process of finding and scaling from a representative gauged catchment. The rainfall-runoff methods are chosen away due to two main reasons. The first is that they require precipitation data, which can be sparse in several areas. This introduces an acquirement and evaluation of data that is not needed in the NIFS formula. The second reason is that they will require the construction of a hyetograph, making the backwards calculations to find flood return period more complex. A hyetograph is only required for PQRUT, but due to the catchment size constraints of the rational method, PQRUT would have to be applied alone or in combination with the rational method to perform flood calculations. Further, the rainfall-runoff methods assume that a rainfall event with a certain return period will result in a flood with the same return period. This assumption is relatively sound with respect to rainfalls-events usually leading to the larger floods in small catchments, but there is still uncertainty connected to it which is avoided by using the NIFS formula. The main assumption made when using the NIFS formula is that the catchment in question has a low degree of regulation and urbanization.

The two equations that make up the NIFS formula is given below; growth curve given by eq. (8) and mean annual flood given by eq. (9) The constant used in the equation for growth curve is given by eq. (10) (Stenius et al., 2015). The return period is found by solving eq. (8) with respect to return period, whose belonging flood size is given by the culvert capacity and the contributions from alternative floodways. All the other variables can be determined independently since they are either catchment parameters or functions of them.

$$\frac{Q_T}{Q_M} = 1 + \frac{0.308\, q_N^{-0.137} [\Gamma(1+k)\Gamma(1-k) - (T-1)^{-k}]}{k} \tag{8}$$

$$Q_M = 18.97\, [0.001\, q_N\, A]^{0.864}\, e^{-0.251\sqrt{A_{SE}}} \tag{9}$$

$$k = -1 + \frac{2}{1 + e^{0.391 + 1.54\, A_{SE}/100}} \tag{10}$$

where

Q_T = Flood with return period T [m^3/s]
Q_M = Mean annual flood [m^3/s]
q_N = Mean specific runoff in the period 1961-90 from runoff map [l/s·km^2]
Γ = The gamma-function
k = Constant
T = Return period [years]
A = Catchment area [km^2]
A_{SE} = Effective lake percentage [%]

The possible effect of climate- and land cover change on the incoming flood is important to consider when studying culvert failure in the future. The literature study in section 2.4.3 shows that there are several methods for modelling their effect, but most of them have a higher complexity than what is aimed for in this work and are difficult to apply in the backwards applications of the NIFS formula. The usage of percentages of change in flood size is therefore applied to model their effect, following the general approach used in climate change adaption planning. Since the NIFS-formula is based on regression of historical values, the flood size is divided by the factor of change given by eq. (12). Eq. (11) gives the flood size whose return period is sought after and is used in eq. (8).

$$Q_T = \frac{Q_{cap} + Q_{alt,out} - Q_{alt,in}}{K_{change}} \tag{11}$$

$$K_{change} = 1 + \frac{K_{climate}}{100} + \frac{K_{cover}}{100} \tag{12}$$

where

Q_{cap} = Critical capacity of culvert [m^3/s]
$Q_{alt,out}$ = Outgoing water to alternative floodways (zero in flood-situation) [m^3/s]
$Q_{alt,in}$ = Incoming water from alternative floodways [m^3/s]
K_{change} = Factor of change [-]
$K_{climate}$ = Change in flood due to climate change [%]
K_{cover} = Change in flood due to land cover change [%]

3.2.4 Summary of method

The culvert failure prediction method will give the return period of the exceeding flood according to the failure definition's requirements to the headwater level in both the flood- and extreme situation for a given culvert. It can model the effects of the failure modes blocking of inlet, blocking of barrel and downstream flooding, the effect of contribution of alternative floodways and the effect of land cover- and climate in terms of a general change in flood size through giving inputs.

It has two types of applications of the fault tree for culvert failure; a qualitative and a quantitative application. The qualitative application is the evaluation of failure mechanisms that shall result in inputs used for failure modes, including contributions from alternative floodways. The quantitative application is the comparison between flood and critical capacity to give return period of the exceeding flood, using the inputs for failure modes and alternative floodways and inputs for land cover- and climate change.

Table 3.7 Methods for calculating culvert capacity and flood return period and their assumptions.

Flow situation	y_{HW} (situation)	Method	Equations and tables	Assumptions
Weir	1.2 H (flood)	Simplified Froude	Eq. (1), (2) and (3)	No energy losses. No headwater velocity.
Orifice	R(extreme)	Orifice equation	Eq. (4) and Table 3.4	Discharge coefficient for square edge headwall is representative.
Full barrel (downstream flooding)	H (flood) and R(extreme)	Energy balance	Eq. (5), (6) and (7) and Table 3.5 and 3.6	Only entrance-, friction- and outlet losses. No head- or tailwater velocity. Square edge headwall is representative. Manning's n values are representative.

Flood return period	Method	Equations and tables	Assumptions
Flood return period	NIFS-formula	Eq. (8) through (12)	Low degree of regulation and urbanization.

Culvert capacity is calculated under the assumption that the culvert is inlet-controlled unless it is specified that the failure mode of downstream flooding occurs. In that case, full barrel flow is modelled and compared to the capacity for inlet control. Consequently, the capacity will be given by modelling weir flow in the flood situation and orifice flow in the extreme situation if downstream flooding does not occur and by the smallest capacity given by inlet control and outlet control with full-barrel flow if downstream flooding occurs. Table 3.7 gives a summary of the methods used for the three flow situations and their assumptions, and the headwater level which the calculations are performed for to give critical capacity. The flood return period is calculated using the NIFS formula with altered flood-size according to inputs for changes in flood due to land cover- and climate change. Assumptions under this formula is also given in Table 3.7.

The method relies on giving inputs for calculations, which is divided between necessary and explorative data. The necessary data must be given in order to drive the method, while the explorative data can be given when exploring culvert failure. Table 3.8 gives an overview these data according to which calculation they belong to. Table 2.2 shows that the necessary data about culvert configuration can be largely found in the national databanks NVDB and BaneData using Vegkart and Banekart. The exception is length, slope and cover height, where estimated or assumed values may have to be used. The necessary data about the catchment can be extracted from the catchment-generation service NVE Nevina if the catchment can be placed on the defined river network or by other means if this is not possible. The explorative data that deals with capacity and contribution from alternative floodways cannot be determined exactly without field studies and must therefore be given based on a floodway analysis or evaluation.

Table 3.8 Necessary and explorative input data for inlet-controlled flow calculations and flood return period calculations and additional data that must be specified if modelling outlet-controlled flow due to downstream flooding.

Calculation	**Necessary data**
Capacity (culvert configuration input)	Shape (box or pipe)
	Diameter / width and height [m]
	Cover height [m]
Flood return period (catchment parameters input)	Mean specific runoff in period 1961-90 [l/s·km^2]
	Area [km^2]
	Effective lake percentage [%]
Calculation	**Explorative data**
Capacity	Blocked inlet [% of height]
	Blocked barrel [% of height]
Flood return period	Outgoing water to alt. floodways [m^3/s]
	Incoming water from alt. floodways [m^3/s]
	Change in flood due to climate change [%]
	Change in flood due to land cover change [%]
Type of data	**Additional data if modelling downstream flooding**
Necessary data for outlet control capacity calculation	Length [m]
	Slope [m/m]
	Material (rough or smooth)
Explorative data	Downstream flooding level [% of height]
	Bed material that blocks barrel (sediments or ice)

The logic of the method is more apparent when applied in a stepwise manner;

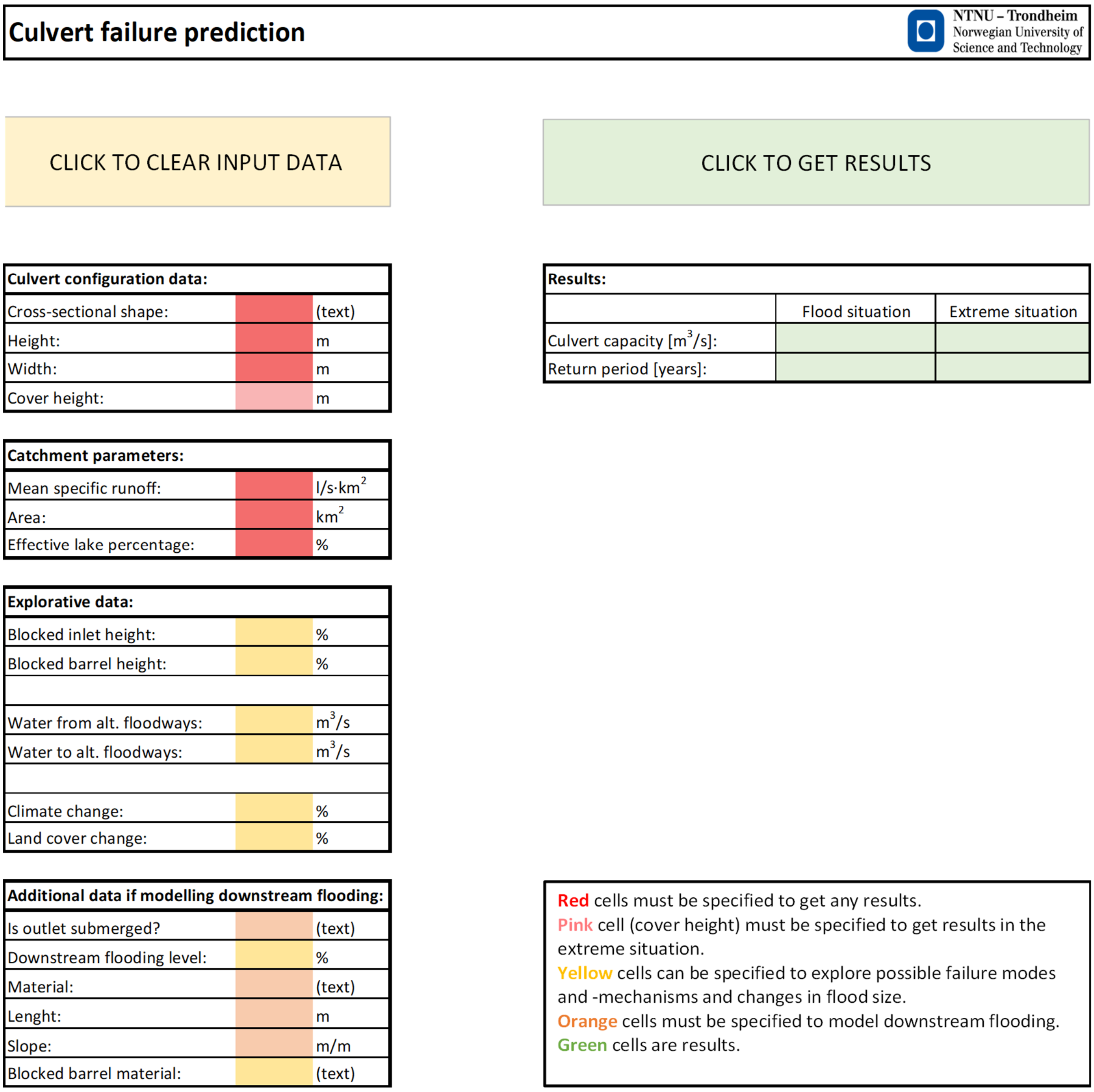
1. Qualitative application of fault tree
    - Establish possible failure mechanisms and their resulting inputs for failure modes, including contributions from alternative floodways.
2. a) Calculation of culvert capacity if downstream flooding does not occur
    - Flood situation: Critical culvert capacity is given by weir flow with headwater level referenced to open inlet $y_{HW,o} = 1.2\ H_{open,i}$ where $H_{open,i}$ is the open inlet height.
    - Extreme situation: Critical capacity is given by orifice flow with headwater level $y_{HW} = R$, where R is the culvert height plus cover height.
2. b) Calculation of culvert capacity if downstream flooding occurs
    - Flood and extreme situation: Calculate critical capacity for full barrel flow with headwater level $y_{HW} = H$ in the flood situation and $y_{HW} = R$ in the extreme situation and a tailwater level given by the downstream flooding level; $y_{TW} = H \cdot \%flood$ where $\%flood$ is minimum 100%.
    - Compare capacity with the one given by inlet control – the smallest gives the final critical capacity.
3. Calculation of flood return period
    - Flood size is given by critical culvert capacity and the contributions from alternative floodways. If climate- and land cover changes are considered, establish the change in flood in percent and adjust the flood size with the resulting coefficient of change.
    - The calculated belonging return period is the output of the method for predicting culvert failure.

3.3 The Excel workbook "Culvert Failure Prediction"

Microsoft ® Excel is a well-known program that many are familiar with and contains many built-in functions for data analyses. Since all the calculations in the culvert failure prediction method can be performed with Excel, it is deemed expedient to code the method in an Excel workbook to make it as practically applicable as possible. This section deals with the creation of the Excel workbook "Culvert Failure Prediction", which is the encoded version of the culvert failure prediction method. The workbook is also tested to make sure that it does not contain any bugs and that the methods behind the prediction provides reasonable results.

3.3.1 Creation of the Excel workbook

The Excel macro-enabled workbook “Culvert Failure Prediction” is created with the aim of being applicable for a user that has not read this work nor has extensive familiarity to hydraulic and hydrologic calculations. It contains three worksheets. The first is “Inputs and Results”, which is where the user specifies inputs with the help of color-coded cells and provided input-, error- and warning messages. A screenshot of this worksheet is given in Figure 3.3.



Culvert failure prediction

Culvert configuration data:		
Cross-sectional shape:	🟥	(text)
Height:	🟥	m
Width:	🟥	m
Cover height:	🟥	m

Catchment parameters:		
Mean specific runoff:	🟥	l/s·km^2
Area:	🟥	km^2
Effective lake percentage:	🟥	%

Explorative data:		
Blocked inlet height:	🟨	%
Blocked barrel height:	🟨	%
Water from alt. floodways:	🟨	m^3/s
Water to alt. floodways:	🟨	m^3/s
Climate change:	🟨	%
Land cover change:	🟨	%

Additional data if modelling downstream flooding:		
Is outlet submerged?	🟧	(text)
Downstream flooding level:	🟨	%
Material:	🟧	(text)
Lenght:	🟧	m
Slope:	🟧	m/m
Blocked barrel material:	🟨	(text)

Results:		
	Flood situation	Extreme situation
Culvert capacity [m^3/s]:	🟩	🟩
Return period [years]:	🟩	🟩

Red cells must be specified to get any results.
Pink cell (cover height) must be specified to get results in the extreme situation.
Yellow cells can be specified to explore possible failure modes and -mechanisms and changes in flood size.
Orange cells must be specified to model downstream flooding.
Green cells are results.

Figure 3.3 Screenshot of worksheet “Inputs and Results”.

Results are provided in the same worksheet by clicking on a macro-assigned textbox, which extracts computational results from the two worksheets “CAPCALC” and “RETURNCALC”. Even though the return period is the main result, the critical capacity of the culvert is also given since it provides an important context for the calculations. The worksheet “CAPCALC” performs critical capacity calculations according to the inputs given while the worksheet

“RETURNCALC” calculates the resulting return period of the exceeding flood, both using the methods described in the previous sections. The screenshots of the worksheets with example values are given in Appendix B.

3.3.2 Testing of Excel workbook

There are two types of tests the Excel workbook “Culvert Failure Prediction” should go through before being used in a case study. The first is a bug test to make sure that the workbook provides expected results and does not contain faulty coding. The second is an uncertainty test to ensure that the methods chosen for estimating capacity and flood provides reasonable results. Both types of tests are included in this study, but the uncertainty test is limited to only testing calculation of design capacity. The uncertainty in the flood estimation is known to be between 0.5 to 2 times the T-year flood (see Table 2.1), which is deemed tolerable and is therefore not further investigated. There is a lack of available data to test the estimation of capacity when the culvert is blocked and changes in flood due to climate- and land cover change. An uncertainty test on these elements are therefore not included since there is a scarcity of time to acquire such data. The results from the bug test and the test on design capacity are given in Appendix C.

The bug test is performed by varying input values and comparing the resulting outputs for return period from the workbook with expected trends and outcomes. A base case with set values for input data is established so that the response to variations in a certain input can be dedicated to only that input. This dedication can be done for all inputs except length, whose variation gives a response that depended on the other inputs. For all inputs, the workbook provided expected results. The bug test is deemed adequately extensive and, as it provided expected results, it is therefore assumed that the workbook performs as it should.

The uncertainty test on design capacity is done through comparing open capacity estimations from the workbook with capacities read from nomograms in FHWA’s *Hydraulic design of highway culverts* (Schall et al., 2012). Since the values are read it is important to note that some of the values and consequently the test results may not be entirely accurate. Box and pipe culverts with both inlet and outlet control are tested for sizes up to 2.5 m. The headwater level is set to 1.2 times culvert height to test weir flow and 3 times height to test orifice flow and a water level difference of 2 m is used to test full barrel outlet control. Figure 3.4 shows plots of the results, and the deviation varies between -47% to +7% with respect to the nomogram capacity. The largest deviations occur for inlet control, which generally decreases as size increase. This deviation may be due to imprecise readings of nomogram values but may also indicate that the methods chosen to model inlet control may overestimate capacity as the deviation is negative. The method used for outlet control provides relatively accurate results. The deviations are deemed tolerable as the level of complexity used is low to reflect the aim of practicality, and followingly no changes in methods for calculating culvert capacity is done.

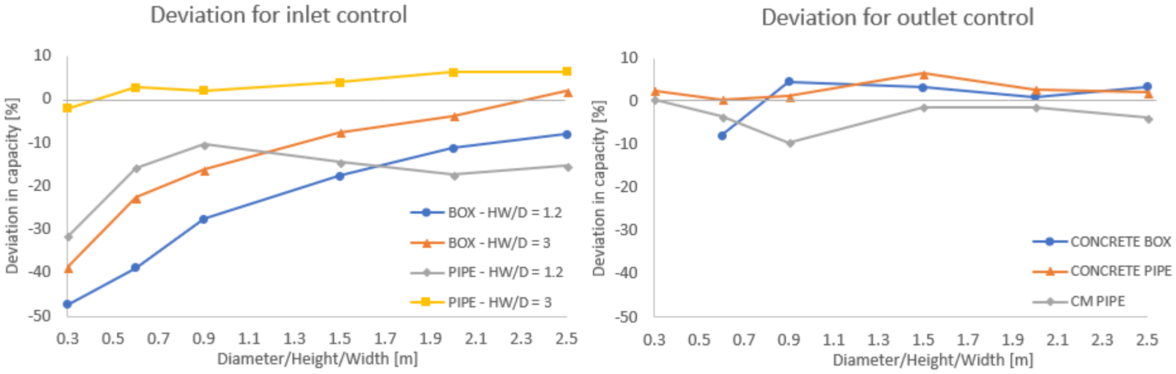


Figure 3.4 Results of uncertainty test on design capacity where deviation in capacity is given as a percentage of the capacity extracted from nomograms.

As the workbook passes both the bug test and uncertainty test on design capacity, it can be used in case studies with the understanding that the uncertainties can be large and that some of methods behind the prediction have not been tested.

3.4 Presentation and preparation of case study

Soknedal is a town in Mid-Norway placed in the southern part of the county Trøndelag. The railway line Dovrebanen and the European route E6, both highly trafficked and important infrastructures in Norway, goes through the town along the rivers Sokna and its tributary Ila, which belongs to the Gaula river system. The rivers have numerous smaller tributaries and their sides are in certain areas very steep and landslides are known to be common in the area. The stretch of Dovrebanen that goes through Sokendal is old and many of the culverts that were installed during its construction in 1919 still stands.

This work looks further into a case study performed by Vauclin (2017) on eight cases of culvert failure in Soknedal that lead to damages on Dovrebanen. The location and belonging catchments of the culverts is shown in Figure 3.5. Vauclin modelled 200-year flood peaks with the parsimonious rainfall-runoff model DDD (Distance Distribution Dynamics), the rational method and the NIFS formula and compared the values with design capacity-estimation provided by Bane NOR. She found that none of the culverts are under-dimensioned, indicating that their capacity was reduced when failure occurred. This is an interesting conclusion that is expedient to dwell further into using the culvert failure prediction method developed in this work.

Figure 3.5 Location and catchments to culverts/damage points where Dovrebanen is marked with a dotted line - from *Use of a parsimonious rainfall-runoff model for flood peak modelling in small ungauged catchments in Norway* (Vauclin, 2017).

Before the case study can be performed, the inputs for the culvert failure prediction method must be established. This is done in the preparation of the case study shown in this section. The necessary input data is first established in the presentation of the study area, both for the culverts and their catchments. The first scientific question deals with occurrence of failure under possible failure modes, thereby requiring an evaluation of failure mechanisms to establish inputs used for failure modes. In this evaluation, the first step in the culvert failure prediction method is used with the qualitive application of the fault tree. The second scientific question deals with the effects of climate – and land cover change, which requires an evaluation to determine the inputs used for changes in flood and alteration in the inputs for failure modes.

The third and last scientific question deals with reducing the occurrence of failure to an acceptable level. Since the culvert failure prediction method is aimed to be used for risk assessments in Norway, Bane NOR's risk acceptance criterion as described in section 2.1.3 is used; the dimensioning flood has a return period of 200 years. This gives that culvert failure can occur with an accepted return period of 200 years, which is used for both the flood- and the extreme situation.

Following the establishment of inputs is a presentation of the structure of the case study, which is the last element in the preparation of the case study. This presentation deals with how the Excel worksheet "Culvert Failure Prediction" is used to provide results that answers the scientific questions through establishing three analyses.

3.4.1 Study area – culverts and catchments

Vauclin (2017) named the eight culverts damage points DP3 to DP10, and their location and catchments are shown in Figure 3.5. Vauclin has extracted the catchment parameters necessary for performing flood-calculations with the NIFS-formula for these catchments, which is further used in this work. The catchments are delineated with NVE Nevina or using the tool QGIS for those that Nevina didn't work for, and the result can be seen in Figure 3.5. The mean specific runoff in the period 1961-90 is extracted from Nevina directly or from neighboring catchments. Land cover data is also extracted and is presented in Table 3.9 for each of the catchments along with the necessary catchment parameters inputs.

Table 3.9 Catchment parameter inputs and land cover data used in case study for the eight culverts, where MSR stands for mean specific runoff - from *Use of a parsimonious rainfall-runoff model for flood peak modelling in small ungauged catchments in Norway* (Vauclin, 2017).

Culvert/ catchment	**Catchment parameters**			**Land cover [%]**		
	Area [km^2]	MSR [l/s·km^2]	Eff. lake perc. [%]	Forest	Cultivated	Marshes
DP3	0.4000	19.6	0	81	9.5	9.5
DP4	0.2000	17.9	0	50	50	0
DP5	0.1432	17.9	0	35	65	0
DP6	0.0626	17.9	0	19	81	0
DP7	0.1400	17.9	0	51	49	0
DP8	0.1108	17.9	0	51	43	6
DP9	0.0659	17.9	0	18	82	0
DP10	2.1900	17.9	0	35	20	45

The necessary culvert configuration inputs that needs to be found depends on whether downstream flooding is modelled or not. A quick overview of the data available in Banekart for the eight culverts shows that length is not given for any of them and that the given slope-values are most likely specified wrong. Further, it is difficult to provide estimations of these values from maps as most of the outlets are difficult to locate. A quick look at a caution map for flood in NVE Atlas shows that only culvert DP10 may be exposed to downstream flooding as the others lie too high up on the steep sides of the rivers. Consequently, only culvert configuration inputs necessary for inlet control calculations are provided for seven out of the eight culverts. For culvert DP10, the outlet can to some extent be located by looking at satellite-pictures. Its length and slope are estimated using a height profile tool in the map solution Høydedata that contains a detailed height model. The created height profile is shown in Figure 3.6.

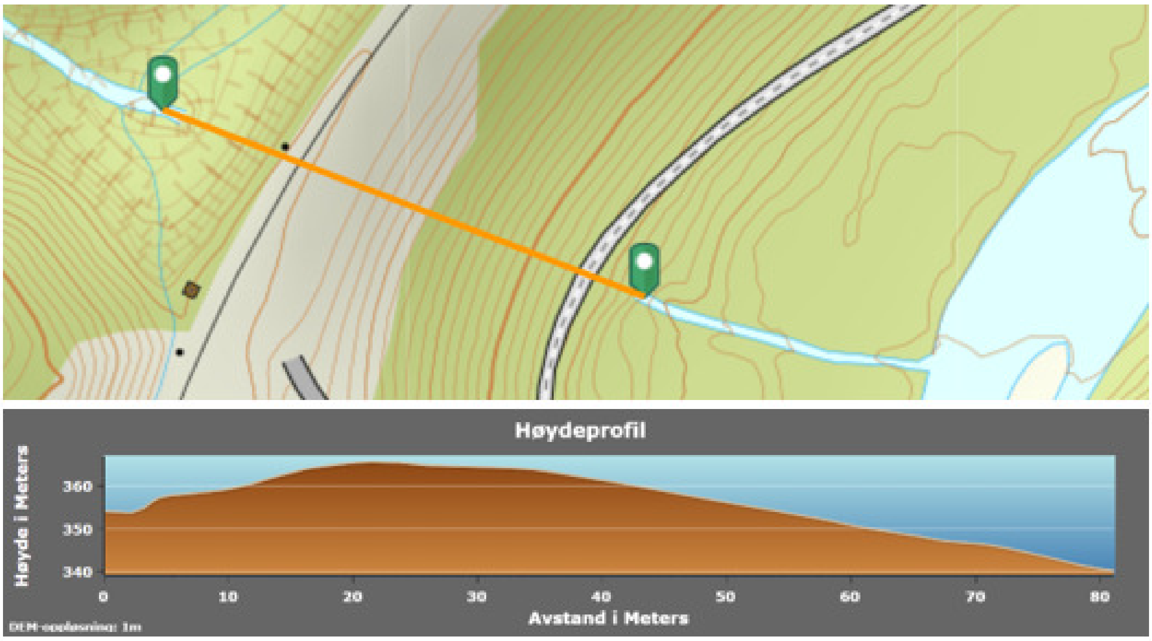


Figure 3.6 Height profile for culvert DP10 created in Høydedata to estimate length and slope.

The extracted culvert configuration input data from Banekart is shown in Table 3.10 along with the estimated length and slope data for culvert DP10. Culvert DP9 is lined with a plastic pipe, and it's the dimension of this pipe that is given. Culvert DP10 has a somewhat unconventional configuration as its inlet-section is an arch in masonry and its outlet-section is a pipe in concrete. Since the culvert failure prediction method cannot be used on arch culverts, it is specified as a pipe culvert in concrete.

Table 3.10 Culvert configuration input used in case study for the eight culverts, including additional data for DP10 to model downstream flooding.

Culvert	Shape	Height [m]	Width [m]	Cover height [m]
DP3	BOX	1.8	1.2	11
DP4	PIPE	1.2	1.2	13
DP5	PIPE	1.0	1.0	16
DP6	BOX	0.6	0.6	8
DP7	BOX	0.8	0.6	7
DP8	BOX	0.9	0.6	4
DP9	PIPE	0.6	0.6	4
DP10	PIPE	2.0	2.0	13

Additional data to model downstream flooding			
Culvert	**Length [m]**	**Slope [m/m]**	**Material**
DP 10	80	0.17	CONCRETE

3.4.2 Evaluation of failure mechanisms and -modes

To establish the inputs used for failure modes, an evaluation of possible failure mechanisms and contributions from alternative floodways is performed. The failure mechanisms that can lead to blocking is first discussed, then the contribution from alternative floodways and finally downstream flooding. The inputs values are chosen to reflect the explorative use of the culvert failure prediction method and are therefore largely based on subjective evaluations.

Blocking of the inlet and barrel due to sediment accumulation is evaluated through looking at soil maps in NVE Atlas. The culverts whose catchments has thick layers of soil are considered to be exposed to sediment accumulation, which Table 3.11 shows applies for all the culverts. As to the degree of blocking, it is assumed that the inlet can become more blocked than the barrel. This is due to that the stream channels generally flattens out when approaching the culvert inlets, so that most of the sediments will be deposited at the inlet. As there is little information to evaluate whether the culverts are self-cleansing, it is assumed that none of them are. It is therefore used a degree of blocking up to 80% at the inlet and up to 50% in the barrel for the culverts exposed to sediment accumulation.

Blocking of the inlet due to slides can give a complete blocking. To evaluate whether slides can occur, the caution maps for soil- and debris slides, rock slides and avalanches in NVE Atlas is used. For the culverts whose inlet is placed within a slide zone, an inlet blocking up to 100% is considered. Table 3.11 shows which of the eight culverts are placed in such zones. Blocking of the inlet due to slides from the embarkment is difficult to directly evaluate since the type of inlet is not given for the eight culverts. A conservative assumption that the inlet may become up to 50% blocked by slides from the embarkment is therefore used for all culverts.

Table 3.11 Culverts exposed to sediment accumulation, slides and lodging by wood shown by whether they are in thick soil layer zones and slide zones and they have a debris rack.

Culvert/ catchment	**Catchment in thick soil layer zone?**	**Inlet in slide zone?**			**Culvert has debris rack?**
		Soil- and debris	Rock	Snow	
DP3	YES	YES	NO	YES	NO
DP4	YES	YES	NO	NO	NO
DP5	YES	YES	NO	YES	NO
DP6	YES	NO	NO	NO	NO
DP7	YES	NO	NO	NO	NO
DP8	YES	NO	NO	NO	NO
DP9	YES	YES	NO	NO	NO
DP10	YES	YES	NO	NO	NO

The data in Banekart for the eight culverts contains information about whether the culverts are installed with a debris rack. As Table 3.11 shows, none of the culverts are. It is therefore assumed that blocking of the inlet due to lodging of wood is to be expected to occur for all culverts. as there are trees in all of the inlet-zones. As with accumulation of sedimentation, a degree of blocking up to 80% is considered.

There is little information to evaluate whether the culverts have ice-problems, but since Soknedal is an area with cold winters it is something may likely occur. Since the streams are generally small and the catchments have no lakes, it is assumed that blocking of the inlet due to ice breakup will not occur. Icing, however, should be considered. A conservative assumption that all the culverts may have a blocked barrel is therefore used, where a degree of blocking up to 80% is used.

To summarize, the inputs used for blocking of inlet is up to 80% for culverts that are not in slide-zones and up to 100% for those that are in such zones. The degree of blocking of barrel is up to 50% when considering blocking by sediments and 80% when considering blocking by ice, which are considered for all culverts.

The contribution of alternative floodways is difficult to evaluate without performing a floodway analysis. Since no such analysis is already performed and available, this is not used in this work. It is assumed that the culverts have no contribution from alternative floodways since they are placed with relatively long distances between other upstream and downstream culverts. However, the quick overview of available data in Banekart shows that some of the culverts have extra floodways installed, whose contribution should be considered. There is little information about the capacity of these floodways. It is therefore assumed that they are culverts with a capacity equal to the design capacity of the culvert they are installed with, which is found from the flood situation estimation given by the Excel workbook "Excel Failure Prediction". Table 3.12 gives which of the culverts that has such extra floodways, and the belonging calculated capacity.

Table 3.12 Culverts with extra floodways and their capacity.

Culvert	DP3	DP4	DP5	DP6	DP7	DP8	DP9	DP10
Extra floodway?	NO	YES	YES	NO	NO	NO	NO	NO
Capacity [m^3/s]	0	2.947	1.868	0	0	0	0	0

Downstream flooding is already established to not occur for any the culverts except DP10. By looking at the downstream terrain, the flood caution map and using the height-profile created to estimate the length and slope of DP10, a maximum downstream flooding level of 400% of the culvert height is estimated as a level that may occur.

The inputs given for degree of blocking and downstream flooding level are maximum values. Inputs up to these values are analyzed to reflect the explorative use of the culvert failure prediction method. It is also done to give a context to the occurrence estimation, as the more severe conditions may have a lower probability to occur.

3.4.3 Evaluation of effects of climate- and land cover change

The potential effects of climate- and land cover change is modelled in the culvert failure prediction method by providing inputs for changes in flood and by altering inputs given for failure modes. The inputs used in the case study is based on the following evaluation.

The change in flood size due to climate change is provided by the recommendations given by Lawrence and Hisdal (2011); a 20% increase should be considered for all catchments smaller than 100 km^2 in Trøndelag. As for land cover, the change in flood depends on the land cover that replaces the existing one. Table 3.9 shows that the existing land cover in the catchments is largely forests and cultivated land, and it is therefore interesting to explore the consequences of urbanization in the area. To provide an estimate of the increase, discharge coefficients given by SVV (2014c) is used; forests and cultivated land has a discharge coefficient of 0.2-0.5 and asphalt and other impervious surfaces of 0.6-0.9. An intermediate estimate of increase in coefficient of 0.5 is chosen, which is assumed to lead to an increase of 50% in flood due to land cover change that follows urbanization.

The theory investigated in section 2.3.2 shows that the effects of climate- and land cover change on the failure mechanisms depends on existing conditions and can lead to both an increase and a decrease in the occurrence and severity of the failure mechanisms. It is assumed that the changes lead to an increase, as this is more interesting to look at from a risk management perspective. However, since the inputs established for the failure modes are very explorative, it is deemed expedient to not directly consider these effects in the calculations and rather keeping in mind that the probability for the more severe states of the failure modes to occur has increased.

3.4.4 Structure of case study

The structure of the case study reflects the scientific questions and the outcomes from the evaluation of failure mechanisms and -modes and of the effects of climate- and land cover change, both in terms of what is analyzed and how it is done.

The evaluation of failure mechanisms and -modes shows that downstream flooding only needs to be considered for one of the culverts (DP10). Consequently, only capacity with assumed inlet control is calculated for the other culverts where blocking of inlet is the only failure mode that has an impact. Since blocking of the barrel gives the same blocking of the inlet, a differentiation of the two is not used. This calculation is also performed for the culvert DP10 to analyze blocking when the outlet is not submerged. The return period is found for blocking degrees with 10% intervals up to 100%, where it is noted which of the culverts have a maximum blocking of 80%. This is called the inlet block analysis from this point.

For DP10, a separate analysis is performed when modelling downstream flooding. The response in return period of a rising downstream water level up to the maximum of 400% with no blocking is first analyzed followed by the response to blocking up to 100% for downstream flooding levels of 100% and 400%. Blocking by both sediments and ice is analyzed, and its noted that maximum blocking by sediments is 50% and ice is 80%, These are compared to the outputs for the inlet block analysis to determine whether downstream flooding has a limiting effect. This is called the downstream flood analysis from this point.

The effects of climate and land-cover change on flood is considered in both the analyses, where four cases are established; no change, climate change (20% increase), land cover change (50% increase) and both changes. The return period for different blocking degrees is found for all four cases in the inlet block analysis while only for increasing downstream flood level in the downstream flood analysis.

For the culverts whose inlet block analysis shows that a return period below the acceptable of 200 years can occur, the degree of blocking that gives a return period of 200 is found. The value is found through performing goal seeking on the failure return period in the Excel workbook “Culvert Failure Prediction” with respect to blocked inlet height. This is done for all the cases of change in flood. The resulting degree of blocking indicates the maximum that is acceptable, which is compared to the blocking degree of 20% set by Bane NOR and SVV to define the maximum before measures must be taken (see section 2.1.3). This is called the acceptable level analysis from this point. The results from the analysis for each of the eight culverts are compared to uncover which of the culverts are most vulnerable to blocking and changes in flood. The acceptable level analysis is not performed on the results from the downstream flood analysis as it cannot be compared to other results.

The three analyses provide the results to answer the scientific questions; the inlet block analysis and downstream flood analysis gives the occurrence of failure under the possible failure modes. The acceptance level analysis provides the maximum allowed degree of blocking and the associated possible failure mechanisms that needs to be addresses to uphold the accepted level. The effects of climate- and land cover change is incorporated in all the analyses through the cases of change in flood and by keeping in mind that the probability for the more severe states of failure modes to occur has increased.

4 Results

The results from the inlet block analysis, the downstream flood analysis and the accepted level analysis described in section 3.4.4 are presented in this chapter, including observations that are deemed interesting. The chapter ends with a short summary of the results to provide a more direct answer to the scientific questions.

4.1 Results from inlet block analysis

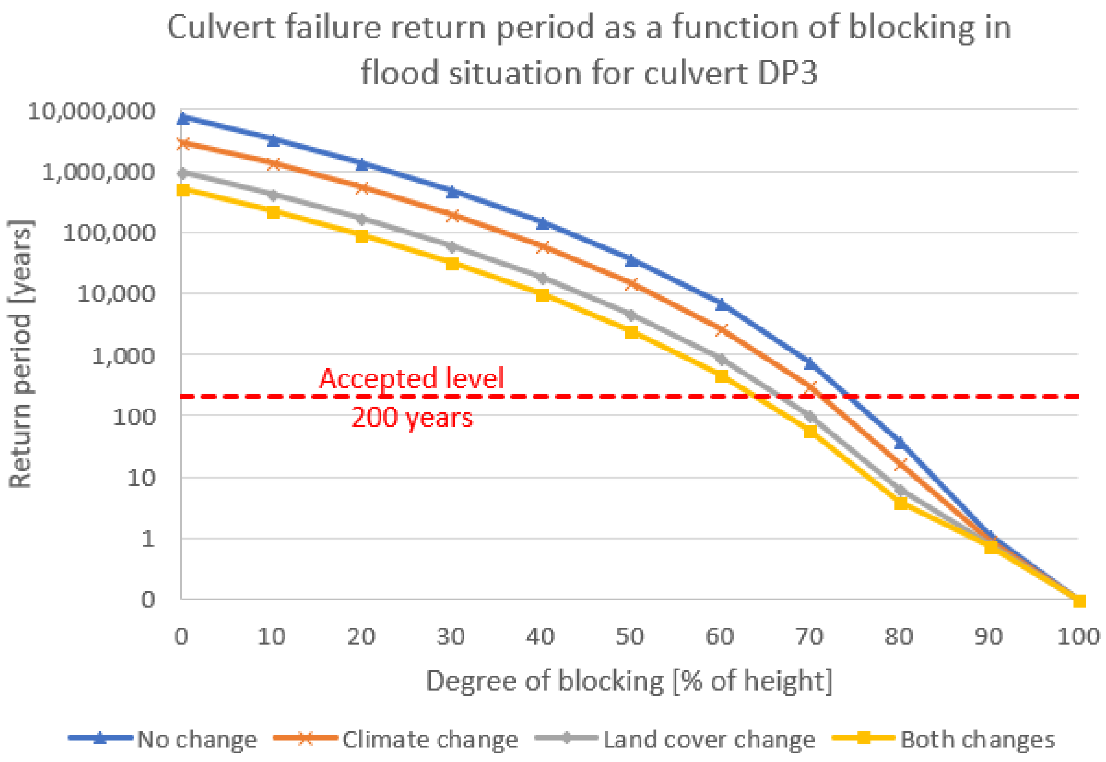
The result from the inlet block analysis is the outputs from the Excel workbook "Culvert Failure Prediction" for increasingly degree of blocking for each of the eight culverts. Graphical presentations of the results are shown in the following figures, while the entirety of the results is given in Appendix D.1. The graphs show the failure return period as a function of blocking, where a logarithmic scale for the return period is used as it provides a more informative presentation of the results that span over several orders of magnitude.

The results for culvert DP3 is shown in Figure 4.1. When the culvert is open, the return period is in the order of millions in the flood situation and in billions in the extreme situation. As the degree of blocking increases, the return period rapidly decreases until reaching zero for complete blocking. However, to get the failure return period below a thousand, the blocking degree must be around 70% in the flood situation and higher than 90% in the extreme situation. This is due to that the rate of change is larger for lower degrees of blocking than higher, as illustrated in Table 4.1.

Table 4.1 Rate of change for culvert DP3 in the flood situation.

Inlet block [%]	10	20	30	40	50	60	70	80	90
Rate of change [years/%]	433935	206207	89470	34567	11462	3080	609	74	4

The effect of changes in flood due to climate- and land cover change for culvert DP3 is a decrease in return period. The case of both changes gives naturally the largest decrease, but this decrease is smaller than the one for the climate- and land cover change combined. At for example 80% blocking, the decrease in return period in the flood situation due to both changes is 36 years while the decrease due to climate- and land cover change alone is 23 and 33 years. Further, as the rate of change is smaller for higher degrees of blocking so is the decrease in return period due to changes in flood. The decrease in return period in the flood situation due to climate change at for example 60% blocking is 4139 years, but at 80% it is 23 years.



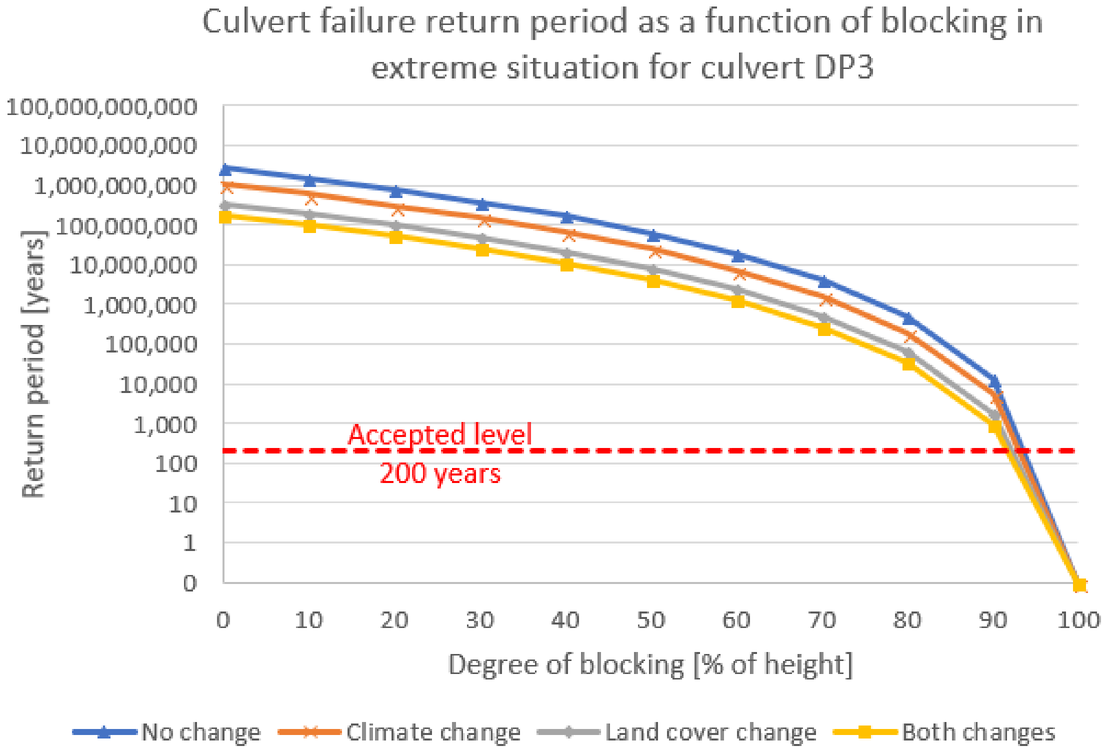
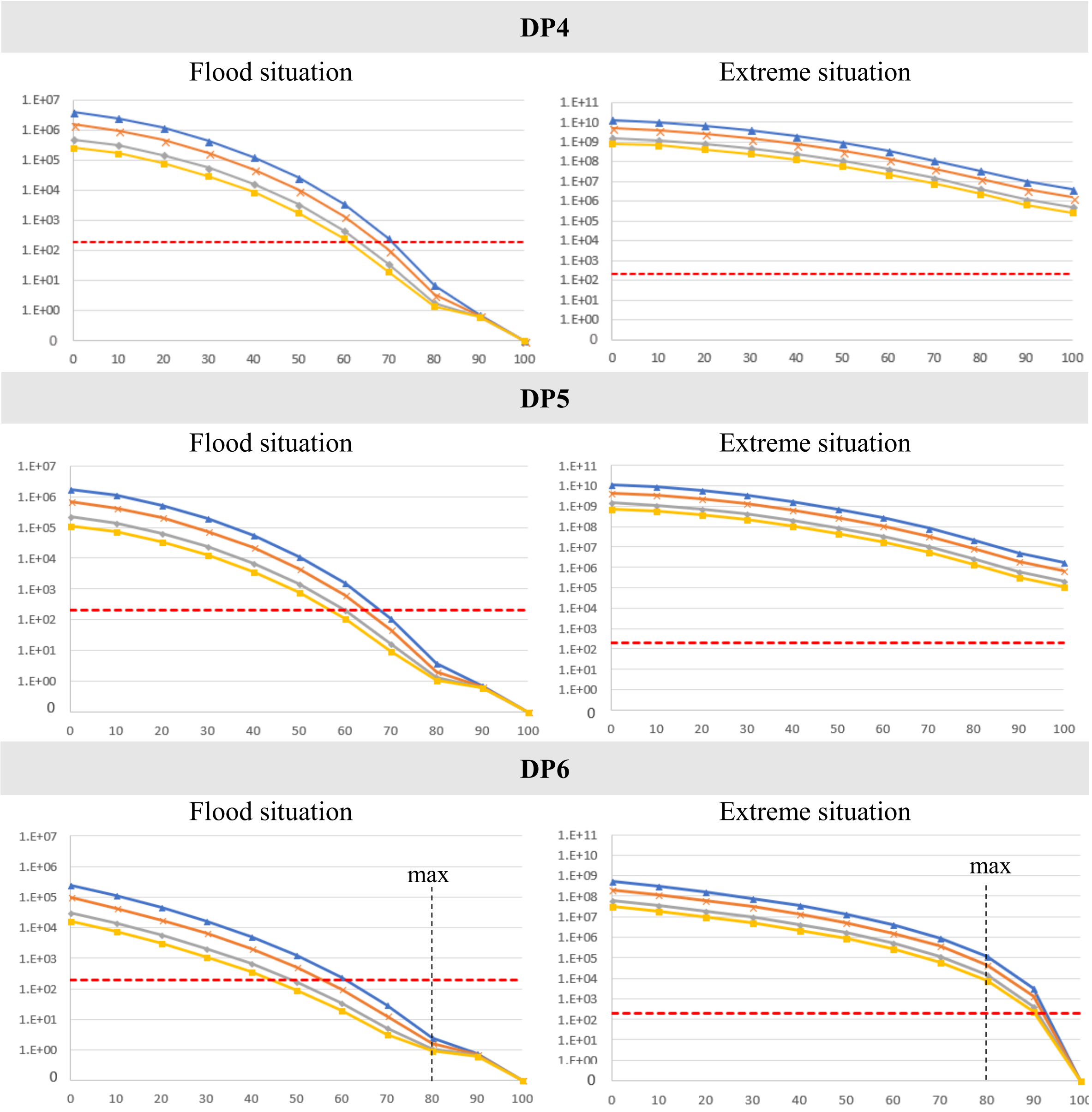


Figure 4.1 Culvert failure return period for culvert DP3 as a function of blocking in the flood- and extreme situation for the four cases of change in flood; no change, climate change (+20%), land cover change (+50%) and both changes. A logarithmic scale is used for the return period, and the accepted occurrence of failure of 200 years is marked with a dotted line.

The results for the other culverts are very similar to those for culvert DP3 and will therefore not be extensively presented. The results are shown in Figure 4.2, where the graphs have the same axis bounds and -units and legend as the graphs for culvert DP3 in Figure 4.1. The largest difference is for the culverts DP4 and DP5 in the extreme situation. The return period never reaches below 200 years, which is due to the contribution from the extra floodways that gives a return period at complete blocking equal to the return period in the flood situation when the culverts are open. Culverts DP6, DP7 and DP8 have a maximum blocking degree of 80% as they are situated outside slide-zones, which is marked in their graphs. Consequently, their smallest return period is not zero as the other culverts, but below 5 years and down to 1 year in the flood situation for some of the cases of changes in flood.



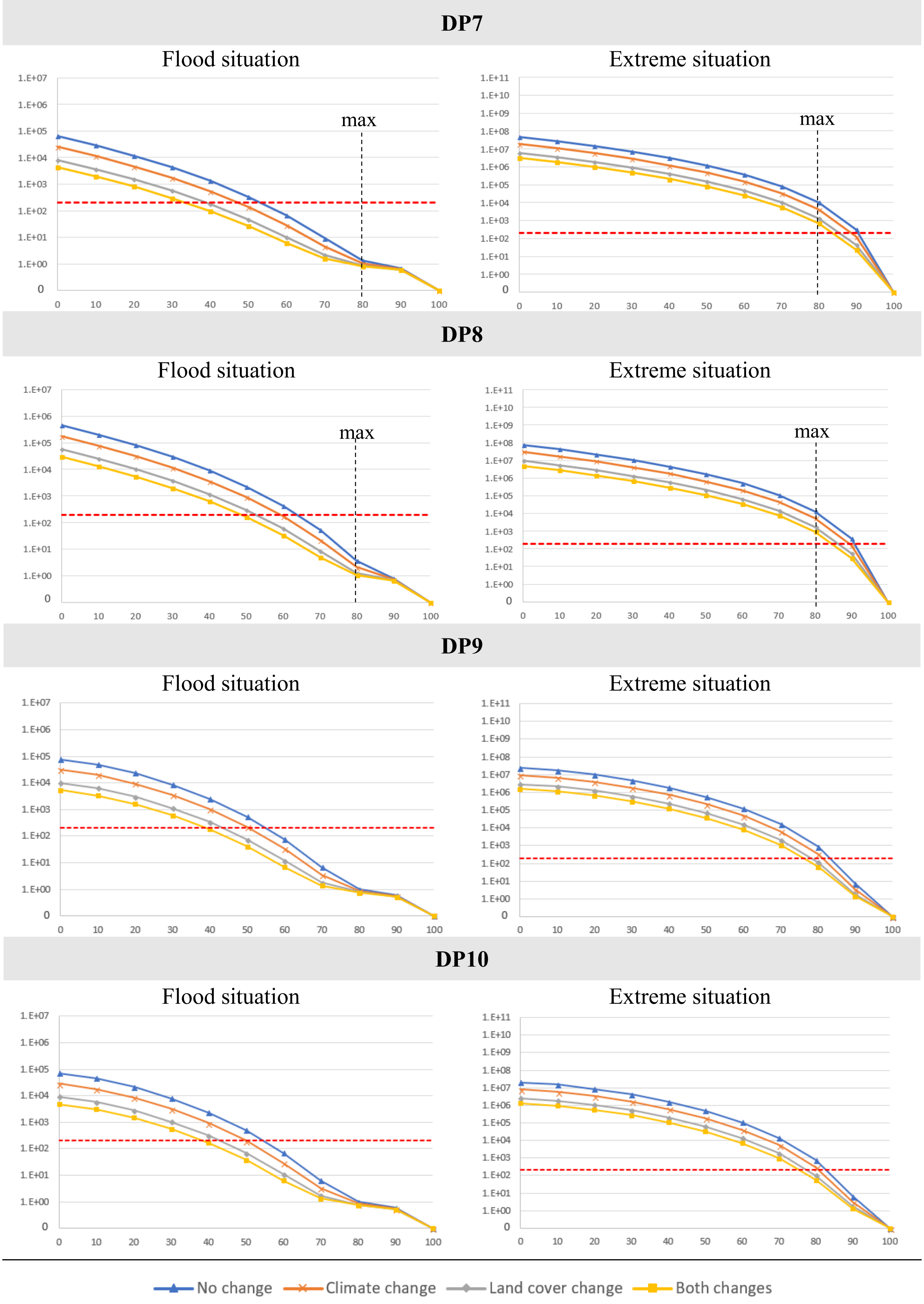


Figure 4.2 Culvert failure return period for culverts DP4 to DP10 as a function of blocking in the flood- and extreme situation for the four cases of change in flood; no change, climate change (+20%), land cover change (+50%) and both changes. A logarithmic scale is used for the return period, and the accepted occurrence of failure of 200 years is marked with a dotted line.

4.2 Results from downstream flood analysis

The result from the downstream flood analysis is the outputs from the Excel workbook "Culvert Failure Prediction" for culvert DP10 where downstream flooding is modelled. Some of the results are presented, including a graphical presentation of the response to blocking of the barrel by sediments and ice with a logarithmic scale for the return period. The entirety of the results is given in Appendix D.2.

The first element in the analysis is the response to a rising downstream water level with no blocking. A comparison with the results from the inlet block analysis shows that downstream flooding has no limiting effect, as the outputs are the same even up to a 400% downstream flood level.

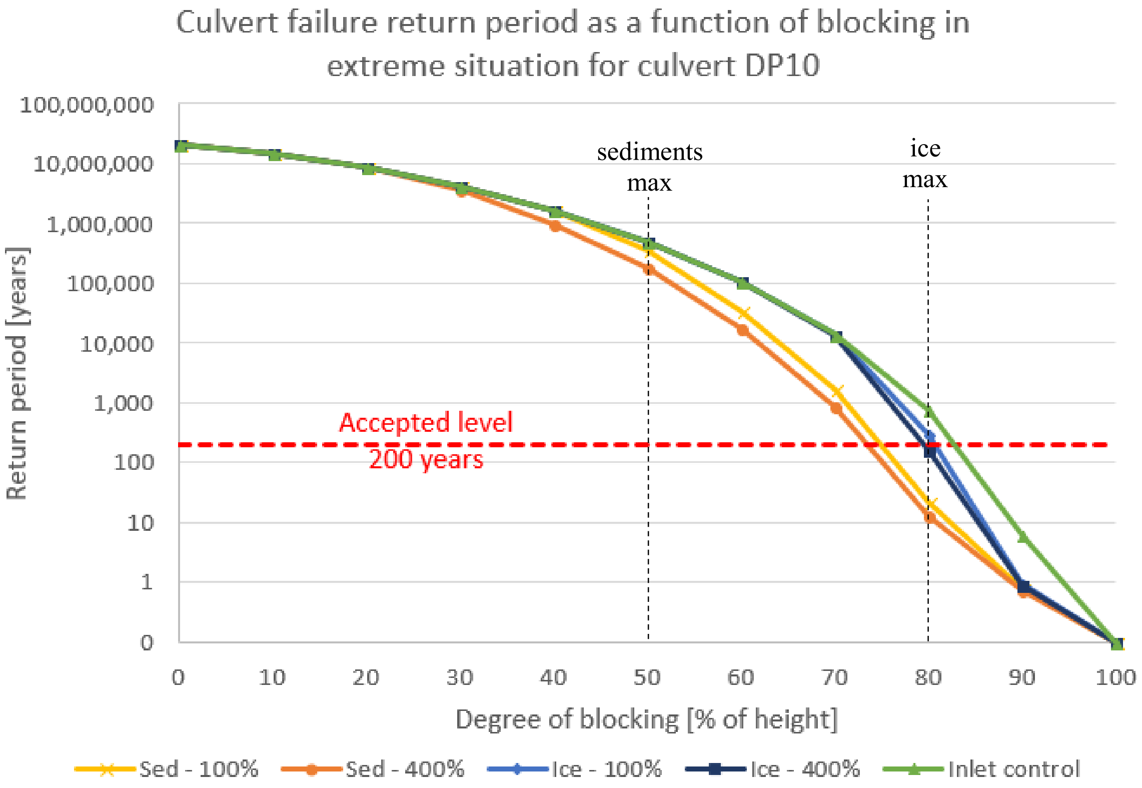


Figure 4.3 Culvert failure return period for culvert DP10 with downstream flooding as a function of blocking in the extreme situation. Blocking by sediments and ice is shown with a 100% and 200% downstream flood level along with the results for DP10 from the inlet block analysis.

The second element in the analysis is the response to increasing degree of barrel blocking with downstream flood levels of 100% and 400%. In the flood situation, the results are the same as for the inlet block analysis, meaning that downstream flooding does not have a limiting effect. In the extreme situation, a decrease in return period occurs compared to the results from the inlet block analysis, which can be seen in Figure 4.3. This decrease does not occur until a certain degree of blocking, which is smaller for sediments than ice. This degree of blocking is below the maximums, which is 50% for sediments and 80% for ice. Downstream flooding has consequently a limiting effect in the extreme situation. Further, a higher downstream flood level will give a lower return period and thereby increases the limiting effect.

4.3 Results from acceptable level analysis

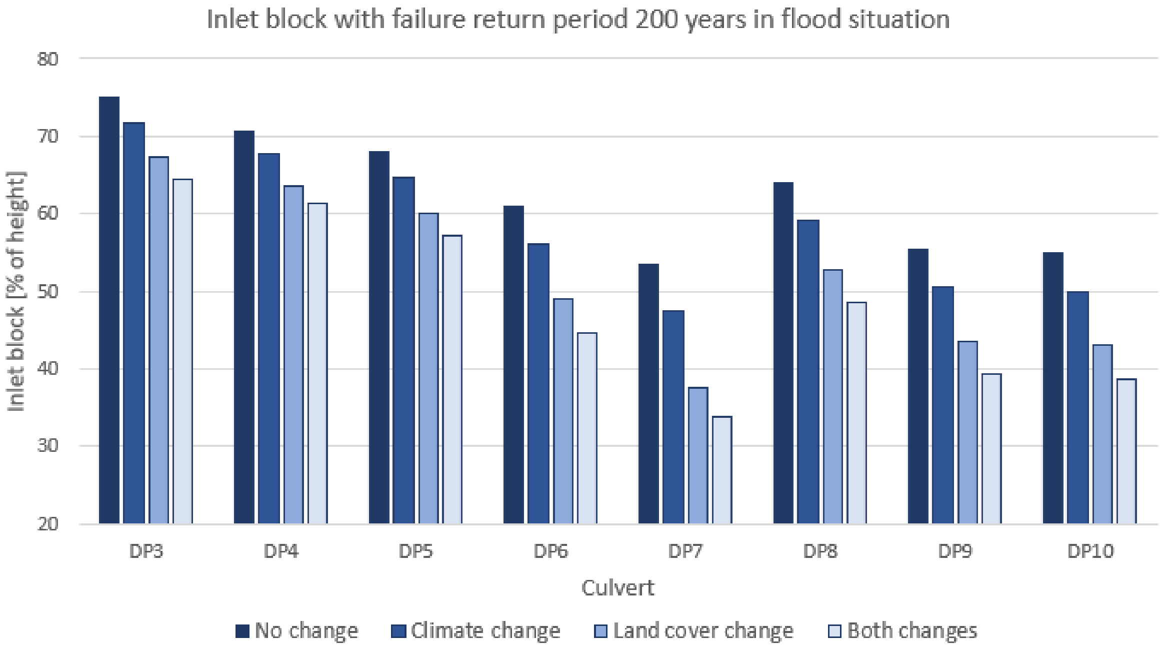
The result from the acceptable level analysis is the degree of blocking that gives a failure return period equal to the acceptable of 200 years. Graphical presentations of the results are shown in the following column charts, and the results for each of the culverts are given in Appendix D.1. Return period below the acceptable can occur for all the culverts except culvert DP4 and DP5 in the extreme situation due to their extra floodways. To present results for all the culverts in both situations, these contributions are not considered in the acceptable level analysis.

The acceptable degrees of blocking that gives a return period of 200 years for the eight culverts is shown in Figure 4.4, found for each of the four cases of change in flood. The degree is smaller in the flood situation than in the extreme situation. The largest degree occurs for culvert DP3 in both the flood- and extreme situation, while the smallest for culvert DP7 in the flood situation and DP10 in the extreme situation. This reflects the general deviation between the rank of culverts in the flood- and extreme situation with respect to accepted degree of blocking. None of the degrees are below the maximum of 20% set by SVV and Bane NOR. For culverts DP6, DP7 and DP8, the acceptable degree of blocking in the extreme situation is above the maximum of 80% as they are not in slide zones. They will consequently will never have a failure occurrence in this situation that is below the acceptable.

The culverts with the lowest acceptable degree of blocking are also the ones most sensitive to changes in flood due to climate- and land cover change, as illustrated in Table 4.2. The exception is culvert DP3, which has a higher mean runoff than the other culverts and therefore will be more affected by the change.

Table 4.2 Culverts sorted according to acceptable degree of blocking in the flood situation and their associated accepted blocking degree with no change and the decrease in this value due to both changes in flood.

Culvert	**DP7**	**DP10**	**DP9**	**DP6**	**DP8**	**DP5**	**DP4**	**DP3**
Acceptable block [%]	53.5	54.9	55.4	61.0	63.9	68.0	70.7	75.0
Decrease [%]	19.8	16.5	16.3	16.1	15.4	10.8	9.4	10.6



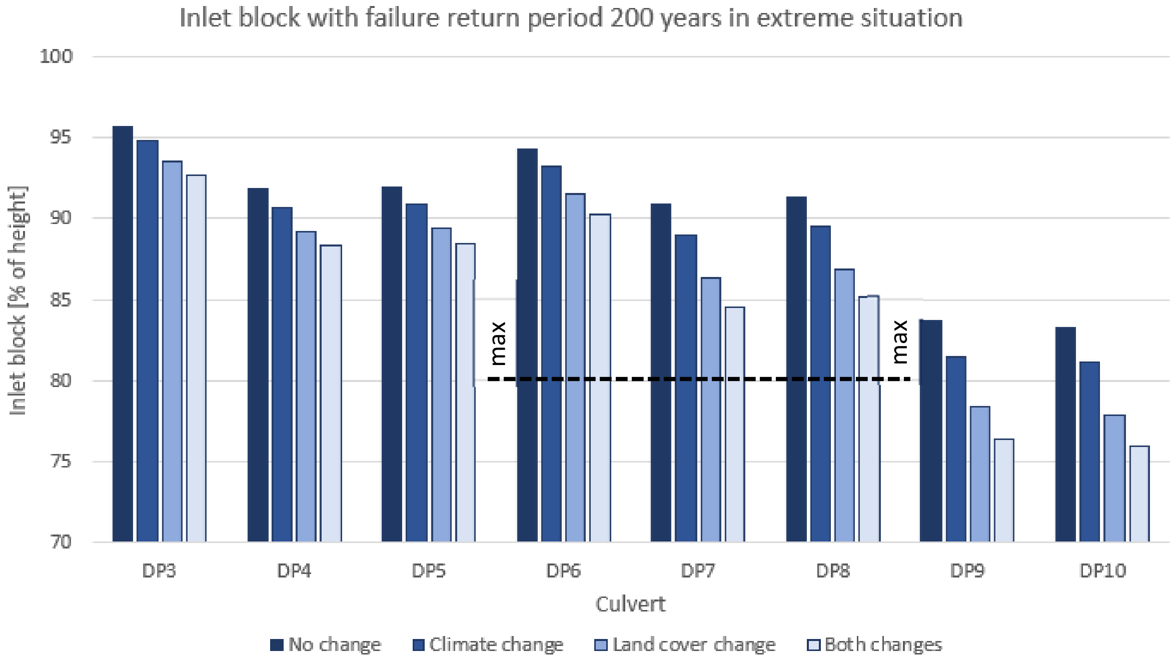


Figure 4.4 Blocked inlet height at return period equal to the accepted of 200 years in the flood- and extreme situation with the four cases of change; no change, climate change (+20%), land cover change (+50%) and both changes.

To determine which of the failure mechanisms that need to be addressed to keep the failure occurrence below the acceptable, the acceptable degree of blocking is compared to the maximum values for the failure mechanisms. We can see that most of the failure mechanisms must be addressed in the flood situation. The accepted degree is below 80% for all the culverts, indicating that blocking by sediment accumulation, wood lodging and ice can give failure below the accepted for all of them. Some of the culverts has a degree below 50%, indicating that sediment accumulation in the barrel and slides from the embarkment can also give failure and that the probability for the formerly mentioned failure mechanisms to give failure has increased. In the extreme situation is the accepted degree above 80% for all the culverts, except for culvert DP9 and DP10 under climate- and land-cover change. This indicates that a slide must occur to give failure below the acceptable, and therefore is the only failure mechanism that need to be addressed in the extreme situation.

4.4 Summary of results

To provide a clear answer to the scientific questions, a summary of the results is presented below in a general manner for the eight culverts.

The occurrence of culvert failure under the possible failure modes varies between being in the order of millions in the flood situation and billions in the extreme situations when the culverts are completely open down to zero when the culverts are completely blocked. The occurrence of failure rapidly decreases following the first degrees of blocking but slows down as the degree increases. For the occurrence of failure to get below 1000 years it must be roughly around 50% in the flood situation and around 80% in the extreme situation. The culverts DP4 and DP5 have an extra floodway, giving a failure occurrence in the extreme situation at complete blocking not equal to zero, but equal to the one for the open culvert in the design situation. The culvert DP6, DP7 and DP8 are not in slide-zones, and has therefore a minimum failure occurrence equal to around 5 years in the flood situation and larger than 10 000 years in the extreme situation. Culvert DP10 can be exposed to downstream flooding, which does not affect the culvert in the flood situation but has a somewhat limiting effect in the extreme situation for blocking degrees close to the maximums for sediments and ice.

The effect of climate- and land cover change on the occurrence of culvert failure is a decrease in the failure return period. The decrease is larger for lower degrees of blocking than the higher. The case of both changes gives the largest decrease, but it is smaller than the combined decrease of climate- and land cover change alone.

The occurrence of culvert failure can be reduced to an acceptable level for all the culverts by keeping the degree of blocking below 30% in the flood situation and below 80% in the extreme situation. To achieve this, all of the failure mechanisms has to be addressed in the flood situation while only slides has to be addressed in the extreme situation.

5 Discussion

The aim of this work is to answer the scientific questions in the case study of Soknedal but the developed method to predict culvert failure is the main product. Consequently, a short discussion of the results from the case study is given and a longer one on using the culvert failure prediction method in risk assessments.

5.1 Case study results

The failure return period when the culverts are open are in the millions in the flood situation and billions in the extreme situation. This indicates that failure in this state is not possible. Further, this suggests that their size has been chosen without considerations to a dimensioning flood. This is likely as the culverts are very old, and has in this case fortunately led to them to be over dimensioned rather than under.

The failure return periods in the extreme situation are extremely high, even up to very high degrees of blocking. This can largely be accredited to the sizable cover heights, which are from 4 to 16 meters. It is unlikely that the headwater rises to such levels as the streams are quite small, and water will probably rather go to other floodways. We can see that for culverts DP4 and DP5, where the contribution from their extra floodway is considered, the failure return periods are in the millions at complete blocking, indicating that failure in the extreme situation will not occur. This will most likely apply for all the other culverts as well. This renders the results for the acceptable level analysis in the extreme situation somewhat irrelevant. The only imaginable scenario where failure in the extreme situation might occur is if a slide of a large mass fills the ditch up to a high level.

The high-up location of the culverts on the steep sides of the rivers makes downstream flooding not an issue. This even applies to the culvert DP10 that has an outlet that may become submerged due to downstream flooding; failure in the flood situation is not affected by a rising of the downstream flood level and failure in the extreme situation will, as mentioned, probably not occur. Culvert DP10 is likely not affected by the downstream flooding due to its large slope and length, causing a hydraulic jump to form in the culvert barrel rather than a damming that reaches the inlet.

The growth curve in the NIFS-formula has a decreasing rate of change with increasing return period which inversely gives a decrease in rate of change in return period with decreasing flood size. This explains many of the result observations. The first is the rapidly decreasing failure return period following the first degrees of blocking which slows down as the degree becomes higher; the capacity and consequently flood size is decreasing. The second is the decrease in failure return period due to climate- and land cover change that is smaller for higher degrees of blocking; the factor of change is constant, giving a smaller decrease in flood size as the capacity decreases. The third is that the case of both changes gives a smaller decrease in failure return period than the combined ones for climate- and land cover change alone; the factor of change for the case of both changes is smaller than the added ones for climate- and land cover change alone, giving a smaller decrease in flood size.

The second observation also explains the results for accepted degree of blocking; the culverts with the lowest accepted degree are also the ones most sensitive to climate- and land cover change. This result is quite interesting in terms of practical consequences. It shows that the culverts that are more likely to fail for smaller degrees of blocking will also be most affected by climate and land-cover change. If the changes additionally increase the probability for more severe states of blocking to occur, these culverts will be very vulnerable.

The accepted degrees of blocking are all above the maximum of 20% set by Bane NOR. If the maintenance routines are in order, only one failure mechanism should in theory be able to give failure for the culverts; slides. Slides are momentary events that can give a degree of blocking above the accepted, and as soil- and debris slides are dominating in the area they will also be combined with heavy rainfall. The other failure mechanisms largely deal with a gradual build-up that should be dealt with before becoming too severe. It is therefore very likely that the cases of failure for the eight culverts that lead to damages on Dovrebanen were due to slides. Culverts DP6, DP7 and DP8 are, however, not in slide-zones. It might be that the caution map for slides is not accurate, but another likely cause is that the maintenance routines are insufficient. Condition assessments on culverts should be performed every 12 months by Bane NOR (see section 2.1.3), which might have been be too sparse or not upheld and performed with longer intervals. It is also important to note that some of the other failure mechanisms can give a quite quick progression of blocking during a large storm unless measures are in place to avoid it. This most notably applies for wood lodging and sediment accumulation at the inlet.

As slides is a problematic issue, measures to reduce the risk of slides should be performed. Such measures are for example the establishment and upkeep of vegetation, which will increase the soil strength. This will also reduce sediment transport, giving less sediment accumulation. Trees too close to the streams should, however, be either cut down or regularly cleared to avoid logs and twigs from lodging at the inlet. As for icing, it should be mapped out for which of the culverts this can occur and followingly either cover their inlets or thaw the ice away each winter.

5.2 Using the culvert failure prediction method in risk assessments

The following discussion deals with whether the developed culvert failure prediction method is a feasible tool in risk assessments of culverts and how it can possibly be used. The performance of the method in the case study is first discussed followed by an assessment of uncertainty in the method's results and lastly a discussion on its potential and critical use.

5.2.1 Performance in case study

The case study can be viewed as the practical test of the culvert failure prediction method to determine whether it is feasible as a desktop study with only the available information at hand. The following is a discussion of the general practicality of the method through its performance in the case study, including obstacles met and how they were potentially solved.

The necessary input data to drive the method reflected very well the amount of available data about the culverts in the case study. The only assumption that had to be made was for the culvert with an arch inlet. This also applied for the catchments that could be delineated with NVE Nevina. However, other tools and assumptions had to be used for many of them as they were very small. As expected, the additional input data required to model downstream flooding was not available, but the detailed height model in Høydedata made it possible to estimate these inputs rather than providing assumed values.

Using map solutions such as NVE Atlas in the qualitative application of the fault tree proved expedient to determine whether the failure mechanisms of downstream flooding, slides, sediment accumulation, ice breaking and lodging by wood could occur. Icing and slides from the embarkment, however, required more information about the culverts which was not available. The contribution from alternative floodways was similarly difficult to establish in the absence of the results from a floodway analysis. The approach used to establish the inputs used for the failure modes was somewhat ungainly as subjective evaluations were used to determine maximum values. Unless it is put an emphasis on the explorative nature of the assessment, such as in the case study, a more scientific approach should be used to determine the expected input-value for the failure mode connected to a mechanism.

The determination of change in flood size in percent due to climate change was quite easy since it only followed recommendations given by NVE. Land cover change proved a bit more challenging, as it is generally not addressed in dimensioning flood calculations. However, the establishment of a scenario and usage of assumptions proved that a value could be provided without having to perform extensive modelling.

The explorative use of the method in the case study required many values to be tested. The workbook “Culvert Failure Prediction” proved to be a valuable tool to get answers quickly, as the result is provided by only clicking a button following the alteration of a value. The simplicity of the method and consequently the workbook also makes the exploration less time-consuming. A higher level of complexity would possibly require more interlinked values having to be changed when studying different scenarios and more computations could give a significant larger running time.

As the results in the extreme situation proved to be of little value, it raises the question whether setting the headwater to a specific level as a part of the failure definition is a suitable approach. On one side, it provides a specific and very clear definition which is expedient in the fault tree analysis. On the other side, it restricts the explorative use of the method as other headwater levels might be more interesting in certain scenarios. However, if the headwater level is treated as an input, a similar ungainly approach as with the failure modes would have to be used if a quick assessment is made. This would not necessarily give results of a more significant value.

5.2.2 Uncertainty in the method

The uncertainty in the results from the culvert failure prediction method is largely unknown as it has only been mapped out for a few elements. It is, however, an important topic that needs to be assessed and is therefore discussed here in a more qualitative and speculative manner. Two elements of uncertainty are presented; the uncertainty connected to the accuracy of the inputs and the uncertainty connected to estimation of capacity and flood.

The accuracy in the culvert configuration inputs depends on the quality and quantity of the data in the databanks. Erroneous registrations will give false results and lacking registrations will lead to estimations or assumptions that may be inaccurate. As the case study shows, both can occur. The accuracy in the catchment inputs largely depends on the tools used to find them and the knowledge the user possesses to evaluate them. NVE Nevina can for example give results that may be erroneous for very small catchments, but an inexperienced user might use these instead of trying again with another tool. The culvert failure prediction method is developed to require a minimum amount of input data. Followingly, the uncertainty connected to the accuracy of input data cannot be decreased by altering the method but by improving the accuracy in databanks and tools used. Additionally, a more experienced user will decrease the uncertainty as the user might detect erroneous data and provide better estimations.

The methods selected to estimate culvert capacity is deemed to provide reasonably accurate results through the uncertainty test on design capacity whose results is presented in section 3.3.2 and Appendix C.2. However, the test shows that the selected methods can overestimate the capacity. Such an overestimation is more critical than an underestimation in a risk assessment since it will lead to failure occurring more often and/or at less severe conditions than expected. So, even though the magnitude of the deviation is acceptable, it has the wrong sign. Further, the uncertainty will likely be larger than the one found in the test for many cases. Firstly, the uncertainty will presumably increase for other inlet configurations than a square edged headwall which is assumed to be representative. Secondly, the uncertainty when the culvert is blocked will in all likelihood be larger than the one found for the design capacity. Thirdly, the culvert is assumed to be inlet-controlled unless it is given to have a completely submerged outlet. This gives an overestimation of capacity for culverts that are actually outlet-controlled. This additional overestimation combined with other elements of uncertainty that gives the same outcome will aggravate the issue of presenting an abated risk. The uncertainty connected to the capacity estimation should generally be further investigated to uncover whether it’s acceptable and what consequences it has for the failure occurrence estimation.

The uncertainty connected to flood estimations using the NIFS-formula given by the NVE guideline described in section 2.4.1 is deemed acceptable. However, as the case study shows, many of the catchments can be smaller than the ones used to develop the regression equations in the NIFS formula. The uncertainty will then be larger than the one given by the guideline and it should be further investigated to uncover whether it’s acceptable. This will also apply for catchments that have a substantial degree of urbanization. The case study also shows that failure return periods well above 1000 years can be given as outputs. As the uncertainty in the flood estimation increases with increasing return period, outputs above 1000 years should generally not be considered as accurate results. It is therefore important to interpret such high return periods as the occurrence of failure being very low rather than happening with intervals equal to the failure return period.

Using constant percentages of change in flood-size due to climate- and land cover change is a very simplified approach that does not reflect the complexity of the change as described in section 2.3 and can consequently give inaccurate results. The projected percentage of change due to climate change is for example larger for higher return periods than lower. The usage of the NIFS-formula to find the altered return period under these changes may also introduce inaccuracies, as it is based on regressions on historical data. There is also uncertainty connected to the projections themselves, not only the approach, as they are future scenarios that may or may not occur. So even though a more complex approach is used there will still be a significant uncertainty in the results.

To summarize, the uncertainties connected to the estimations of capacity and flood can be quite large and many elements in the estimations should be further investigated to both uncover the extent of the uncertainty in the method and understand their consequence in a risk assessment. The large uncertainties are rooted in the choice of using estimation methods with low complexity, following the aim of practicality. A higher level of complexity may give more accurate results, but it would have to be applied to all the estimations to give an effect on the accumulative uncertainty. This would likely render the method less practical. However, the loss of practicality must be paid if the uncertainties are deemed unacceptable.

5.2.3 Potential and critical use of the method

The culvert failure prediction method can potentially be a very insightful tool in risk assessments. The culvert failure fault tree provides information about how water-driven failure may possibly occur and the workbook "Culvert Failure Prediction" makes it possible to evaluate the capacity of a culvert in various situations in a way that can be easily compared to the dimensioning criteria. The workbook is also developed to be user-friendly, as it requires neither extensive hydrological and hydraulic knowledge nor having to read this work to be used.

The culvert failure prediction method doesn't necessarily replace the current Norwegian risk assessment methods described in section 2.1.3. They have many similar elements and the method can provide a better foundation for the assessments made. The clearest use of the method is in the second level of the risk- and vulnerability analysis of SVV. Instead of using a residual design capacity of 50% as a benchmark for acceptable risk, the failure occurrence under possible failure modes can be found and compared to the acceptable return period. The differentiation between the flood- and extreme situation also provides a better context of the consequences of a potential failure, and the two situations can for example define consequence levels in a risk matrix (see Figure 2.1). The condition assessment from inspections is an element that will complement the method. The assessment can provide better estimations for failure mode inputs, and the fault tree can be used to uncover which failure mechanisms that can be the cause of the culvert's condition. This will help determine which measures that has to be taken to avoid future failure.

The culvert failure prediction method can also be used when designing new culverts. The fault tree presents many of elements that needs to be considered when designing a culvert in a clear and visual way, so that possible failure mechanism can be addressed before they even occur. The "Culvert Failure Prediction" workbook can be used as an addition to the traditional design capacity- and flood calculations if there are failure mechanisms that cannot be avoided. It can for example be used to determine whether a culvert needs to be over dimensioned or an extra floodway needs to be installed, and if so their necessary dimensions to keep the occurrence of failure below the accepted. New culverts should also be designed with future changes in flood in mind, which is an issue that is addressed in the method. By accounting for changes in flood due to possible land cover changes in addition to climate change, one can make sure that the culvert is able to accommodate future flood situations.

The usage of the culvert failure prediction method in risk assessments requires a critical mindset to avoid misinterpreting its results. This includes understanding the implications of the failure definition, which elements that are modelled and what the results refers to and their accuracy.

The failure definition, which is the foundation of the method, deals with rising of the headwater above the levels that are considered safe. Failure will therefore not necessarily prove a danger to life and health in itself but is rather the cause of other events than can lead to such dangers. The exception is failure in the extreme situation, which can lead to reduced drivability and safety due to the water flowing across the road or railway. Not all the risks connected to culverts are covered in the failure definition, the most notable ones being local scouring at the outlet and structural collapse due to deterioration. Additionally, the failure modes of deterioration and a blocked outlet that can give a reduction in capacity is not modelled in the method. So even though the method implies the risk to be acceptable, this will not necessarily be the case.

The result of the method, the failure return period, refers only to the return period of the exceeding flood. It must therefore not be confused with being the failure probability since the probability for other failure mechanisms to occur is not considered. The uncertainties in the method can also be quite large, as discussed in section 5.2.2. The results should therefore be viewed as rough estimations rather than accurate predictions of how often failure will occur.

6 Conclusion and recommendations

The case study in Soknedal performed in this work is on the same eight culverts on the railway line Dovrebanen studied by Vauclin (2017). The case study supports Vauclin's findings that their failure was not due to the culverts being under dimensioned. Estimations of failure occurrence interval when the culverts are open are well above the acceptable of 200 years set by Bane NOR. Occurrences below 200 years does not arise unless the culverts are under the failure mode of blocking. The blocking degree that gives such an occurrence is, however, larger than what is set as the maximum by Bane NOR before measures must be taken. This indicates that the failures were either due to slides, which is common in Soknedal, or that the maintenance is inadequate. The latter is likely with the significant maintenance backlog for roads and railways in Norway. Another finding from the case study is that the culverts who fails for smaller degrees of blocking will also be the ones most sensitive to changes in flood due to climate- and land cover change. This shows that the culverts most vulnerable to the maintenance backlog are also the ones most vulnerable to the effects of climate- and land cover change. Improvement in maintenance and measures to reduce the risk of slides will consequently keep the occurrence of failure below the acceptable both in the immediate and far future.

The developed method used to estimate the failure occurrence in the case study is the main product of this work. It continues using the two main elements from the framework developed by Kalnes (2017); its failure definition and basing the prediction on the usage of a fault tree. The culvert failure definition is exceedance of critical capacity, which is given by the headwater level considered safe. It is further defined on two levels planning to provide a context to the consequences of a potential failure. The fault tree is used to both uncover the causes of failure and to provide the logic behind estimating failure occurrence through flood return periods. The fault tree in the framework is deemed somewhat flawed, and a new fault tree is therefore constructed in this work. The comparison between incoming flood and culvert capacity is clearly showed in the new fault tree, where one its most important elements is the failure modes that can cause a reduced capacity and their associated mechanisms.

The culvert failure prediction method largely fulfills its aim of being a practical tool in risk assessments and being feasible as a desktop study. This is proved by its performance in the case study; it is able provide insightful information without extensive data and complex computations. The main shortcoming of the method is the determination of inputs used for failure modes which, in the case study, is based on qualitative assessments and evaluations using map solutions provided by the Norwegian Water Resources and Energy Directorate

(NVE). This is a somewhat ungainly approach, and a more scientific technique should be used in the future to determine excepted values unless there is an emphasis on the explorative manner of the assessment.

The culvert failure prediction method is argued in this work to provide better risk estimations than those currently used by the Norwegian Public Roads Administration (SVV) and Bane NOR, as it is able to provide clearer and more quantitative results. The encoded version of the method in the form of the Excel workbook called "Culvert Failure Prediction" provides insightful information about a culvert's capacity under various situations in a way that can be easily compared to the dimensioning criteria and can be used without having to read this work as it is quite user-friendly. The method and the workbook does not have to replace the current assessment approach as they largely complement each other. They can rather prove to be an additional and insightful tool in the assessments made.

The results from the culvert failure prediction method has potentially large uncertainties connected to them, which is rooted in the choice of using estimation methods with low complexity to achieve the aim of practicality. The extent of the uncertainty in the method should be further investigated, as it only has been uncovered for some of its elements. This can for example be done by finding well-documented cases of culvert failure, where all the inputs and outputs of the method is known. Such cases could not be uncovered in this work and would possibly require laboratory studies as it is likely that the extent of data required is not available from field studies. If the uncertainties are found to be unacceptable, potential alterations to the method should be done with the aim of increasing accuracy without considerable loss of practicality.

The results from the method should be viewed as rough estimations rather than accurate predictions of how often failure will occur. This is due to the foundations of the prediction as much as the uncertainty in the method itself. The failure definition of exceedance critical culvert capacity does not cover all the causes behind culvert failure, the most notable ones being outlet scouring and structural collapse due to deterioration. Additionally, not all of the failure modes that can lead to an exceedance of capacity is modelled; reduction in capacity due blocking of outlet and deterioration is not included. These lacking elements must be included to be able to predict all cases of culvert failure. Further, the estimation of failure occurrence refers only to the return period of the exceeding flood. If the goal of the risk estimation is to find the failure probability, alterations to the method must be made. The fault tree for culvert failure constructed in this work can potentially be used, where probability estimations can be found for the different failure mechanisms.

Independently of whether the culvert failure prediction method is deemed to provide beneficial risk estimations, this work has achieved its aim of providing a better understanding of the risk connected to culverts. By investigating theory and literature from many different sources, a wider and more coherent image of the risk and how it can be possibly modelled is provided. By performing a fault tree analysis, the concept of culvert failure is both better defined and understood.

This work has contributed with a method, or at least a foundation, that can hopefully be used to reach Klima 2050's aim of providing better risk estimations in stormwater management. It may also prove to be an aid to reduce the risk connected to water-related hazard events on roads and railways, and consequently to avoid large costs to society from structural damages and loss of life and health.

References

Andersen, J. H., Hjukse, T., Roald, L. & Sælthun, N. R. (1983) *Hydrologisk modell for flomberegninger.* (NVE-rapport 2-83). Norges vassdrags- og energidirektorat (NVE). Available at: http://publikasjoner.nve.no/rapport/1983/rapport1983_02.pdf (accessed: 23.03.2018).

Asvall, R. P. & Hoseth, K. A. (2010). Kapittel 3: Is i vassdrag. In Norges vassdrags- og energidirektorat (NVE) (ed.) *Vassdragshåndboka: håndbok i vassdragsteknikk*: Bokforslaget.

Aven, T. & Renn, O. (2010) *Risk management and governance : concepts, guidelines and applications*. Risk, Governance and Society, vol. volume 16. Berlin: Springer. Available at: https://link.springer.com/content/pdf/10.1007%2F978-3-642-13926-0.pdf (accessed: 16.10.2017).

Bane NOR. (2011). Forskjell mellom versjoner av «Underbygning/Prosjektering og bygging/Drenering». Available at: https://trv.banenor.no/w/index.php?title=Underbygning/Prosjektering_og_bygging/Drenering&diff=prev&oldid=13477 (accessed: 26.02.2018).

Bane NOR. (2014a). Teknisk regelverk - Underbygning/Prosjektering og bygging. Available at: https://trv.jbv.no/wiki/Underbygning/Prosjektering_og_bygging (accessed: 23.03.2018).

Bane NOR. (2014b). Teknisk regelverk - Underbygning/Vedlikehold. Available at: https://trv.jbv.no/wiki/Underbygning/Vedlikehold (accessed: 10.02.2018).

Berggren, L., Erichson, P. S. & Larsen, J. O. (2015) *ROS--analyser i Arealplanlegging.* (NIFS-rapport 62). Oslo: Norges vassdrags- og energidirektorat (NVE). Available at: http://publikasjoner.nve.no/rapport/2015/rapport2015_62.pdf (accessed: 20.02.2018).

Bradley, J. B., Richards, D. L. & Bahner, C. D. (2005) *Debris Control Structures – Evaluation and Countermeasures.* (Hydraulic Engineering Circular 9 FHWA-IF-04-016). Salem: Federal Highway Administration (FHWA). Available at: https://www.fhwa.dot.gov/engineering/hydraulics/pubs/04016/hec09.pdf (accessed: 07.12.2017).

Cafferata, P., Spittler, T., Wopat, M., Bundros, G. & Flanagan, S. (2004) *Designing Watercourse Crossings for Passage of 100 Year Flood Flows, Wood, and Sediment.* (Calefornia Forestry Report No. 1). Sacramento: California Department of Forestry and Fire Protection. Available at: http://www.calfire.ca.gov/resource_mgt/downloads/reports/ForestryReport1.pdf (accessed: 31.10.2017).

Cagle, R. (2003). Infrastructure asset management: An emerging direction. *AACE International Transactions*: PM21-PM26.

Clarkin, K., Keller, G., Warhol, T. & Hixson, S. (2006) *Low-Water Crossings: Geomorphic, Biological, and Engineering Design Considerations.* U.S. Department of Agriculture. Available at: https://www.fs.fed.us/t-d/pubs/pdf/LowWaterCrossings/LoWholeDoc.pdf (accessed: 23.02.2018).

DSB. (2017) *Samfunnssikkerhet i kommunens arealplanlegging - Metode for risiko- og sårbarhetsanalyse i planleggingen.* (DSB veileder). Direktoratet for samfunnssikkerhet og beredskap (DSB). Available at: https://www.dsb.no/globalassets/dokumenter/veiledere-handboker-og-informasjonsmateriell/veiledere/samfunnssikkerhet_i_kommunens-arealplanlegging_metode-for-risiko_og_saarbarhetsanalyse.pdf (accessed: 20.02.2018).

E Tucker, G. & Slingerland, R. (1997). Drainage basin responses to climate change. *Water Resources Research*, 33 (8): 2031-2047.

Eidsvig, U. M. K. (2014) *Sammenligning av risikoakseptkriterier for skred of flom - Utredning for Naturfareprogrammet (NIFS).* (NIFS-rapport 26/2014). Trondheim: Norges Geotekniske Institut (NGI). Available at: http://publikasjoner.nve.no/rapport/2014/rapport2014_26.pdf (accessed: 24.10.2017).

Eikenæs, O., Njøs, A., Østdahl, T. & Taugbøl, T. (2000) *Flommen kommer... Sluttrapport fra HYDRA - et forskningsprogram om flom.* Oslo: Norges vassdrags- og energidirektorat (NVE). Available at: http://publikasjoner.nve.no/hydra/diverse/flommenkommer.pdf (accessed: 08.03.2018).

Ellis, E. (2013). *Land-use and land-cover change*. Available at: https://editors.eol.org/eoearth/wiki/Land-use_and_land-cover_change (accessed: 07.03.2018).

French, R. H. (1987). *Open-channel hydraulics*. Singapore: McGraw-Hill.

Glad, P. A., Reitan, T. & Stenius, S. (2015) *Nasjonalt formelverk for flomberegning i små nedbørfelt.* (NIFS-rapport 13/2015). Oslo: Norges vassdrags- og energidirektorat (NVE). Available at: http://www.naturfare.no/_attachment/832464/binary/1025317 (accessed: 22.03.2018).

Haaland, L. (2002). Slurv med stikkrenner. *Teknisk Ukeblad*. Available at: https://www.tu.no/artikler/slurv-med-stikkrenner/221136 (accessed: 05.03.2018).

Hanssen-Bauer, I., Drange, H., Førland, E., Roald, L., Børsheim, K., Hisdal, H., Lawrence, D., Nesje, A., Sandven, S. & Sorteberg, A. (2015) *Klima i Norge 2100: Kunnskapsgrunnlag for klimatilpasning oppdatert i 2015.* (NCCS report 2/2015). Oslo: Norsk klimaservicesenter (NKSS). Available at: http://www.miljodirektoratet.no/Documents/publikasjoner/M406/M406.pdf (accessed: 05.03.2018).

Holmqvist, E. (2010). Kapittel 2: Hydrologi. In NVE (ed.) *Vassdragshåndboka: håndbok i vassdragsteknikk*: Bokforslaget.

Høydal, Ø. A., Breien, H. & Sandersen, F. (2013) *Prosjektet skog og skred - Forslag til kriterier for vernskog mot skred.* Norges Geotekniske Institutt (NGI). Available at: https://www.landbruksdirektoratet.no/no/eiendom-og-skog/skog-og-klima/vernskog/publikasjoner/forslag-til-kriterier-for-vurdering-av-skog-som-vernskog-ngi-20120078-01-r (accessed: 07.03.2018).

JBV. (2014) *Kapasitetsberegning og tiltaksvurdering av stikkrenner på DB482,2-498,555.* Trondheim: Jernbaneverket (JBV).

Jenssen, L. (1998) *Assessing infrastructure vulnerability to major floods*. Doctoral dissertation. Trondheim: Norwegian University of Science and Technology.

Juliano, T. M., Meegoda, J. N. & Banerjee, A. (2007). *Hydraulic Capacity of Deteriorated Culverts and Impact on Asset Management*. 86th Annual Meeting of Transportation Research Board, Washington DC.

Kalnes, H. (2017) *Framework for predicting culvert failure during a T-year flood.* Trondheim: Norwegian University of Science and Technology (NTNU).

Kiersch, B. & Tognetti, S. (2002). Land-water linkages in rural watersheds: Results from the FAO electronic workshop. *Land Use and Water Resources Research*, 2.

Lawrence, D. & Hisdal, H. (2011) *Hydrological projections for floods in Norway under a future climate.* (NVE Report 5/2011). Oslo: Norwegian Water Resources and Energy Directorate (NVE). Available at: http://publikasjoner.nve.no/report/2011/report2011_05.pdf (accessed: 05.03.2018).

Meld. St. 33 (2016-2017). (2017). *Nasjonal transportplan 2018–2029.* Samferdselsdepartementet. Oslo.

Myrabø, S., Viklund, M., Øvrelid, K., Øydvin, E. K., Petkovic, G., Humstad, T., Aunaas, K., Thakur, V. & Dolva, B. K. (2016) *NIFS final report 2012-2016.* (NIFS Report 92/2016). Oslo: Norwegian Water Resources and Energy Directorate (NVE). Available at: http://www.naturfare.no/_attachment/1659339/binary/1154523 (accessed: 15.10.2017).

Najafi, M., Salem, S., Bhattachar, D., Selman, B., Patil, R. & Calderon, D. (2008) *An asset management approach for drainage infrastructure and culverts.* University of Wisconsin-Madison: Midwest Regional University Transportation Center - Wisconsin Department of Transportation. Available at: https://minds.wisconsin.edu/handle/1793/53919 (accessed: 04.03.2018).

Norem, H. (2016) *Overvannshåndtering bør planlegges for tre nivåer.* (Intervju i VA-forum 2/2016). Oslo. Available at: http://vaforum.no/ckfinder/userfiles/files/VAforum_2%202016.pdf (accessed: 30.11.2017).

Norem, H., Flesjø, K., Sellevold, J., Lund, M. R. & Viréhn, P. L. E. (2016) *Overvannshåndtering og drenering for veg og jernbane.* (NIFS-rapport 28/2016). Oslo: Norges vassdrag- og energidirektorat (NVE). Available at: http://publikasjoner.nve.no/rapport/2016/rapport2016_28.pdf (accessed: 29.09.2017).

NVE. (2008) *Flomsonekartlegging.* (Fakta 2/2008). Norges vassdrags- og energidirektorat (NVE). Available at: http://publikasjoner.nve.no/faktaark/2008/faktaark2008_02.pdf (accessed: 30.11.2017).

NVE. (2014) *Sikkerhet mot skred i bratt terreng.* (Veileder 8/2014). Oslo: Norges vassdrags- og energidirektorat (NVE). Available at: http://publikasjoner.nve.no/veileder/2014/veileder2014_08.pdf (accessed: 28.02.2018).

Rinde, T., Njøs, A. & Grønlund, A. (2000) *Virkningen av arealbruksendringer på avrenningsforhold.* (HYDRA-rapport N05). Oslo: Norges vassdrags- og energidirektorat (NVE). Available at: http://publikasjoner.nve.no/hydra/rapport/n05.pdf (accessed: 06.03.2018).

Schall, J. D., Thompson, P. L., Zerges, S. M., Kilgore, R. T. & Morris, J. L. (2012) *Hydraulic design of highway culverts - Third edition.* (Hydraulic Design Series 5 FWHA-HIF-12-026). Federal Highway Administration (FHWA). Available at: http://www.fhwa.dot.gov/engineering/hydraulics/pubs/12026/hif12026.pdf (accessed: 13.03.2018).

Sivertsen, J. T. (2018). *Nordlandsbanen henger i løse lufta* [photo]. Available at: https://www.nrk.no/nordland/nordlandsbanen-henger-i-lose-lufta-_-fortsatt-skredfare-1.14018002 (accessed: 22.04.2018).

Stenius, S., Glad, P. A. & Wilson, D. (2014) *Karakterisering av flomregimer.* (NIFS-rapport 35/2014). Oslo: Norges vassdrags- og energidirektorat (NVE). Available at: http://publikasjoner.nve.no/rapport/2014/rapport2014_35.pdf (accessed: 23.02.2018).

Stenius, S., Glad, P. A., Wang, T. K. & Væringstad, T. (2015) *Veileder for flomberegninger i små uregulerte felt.* (Veileder 7/2015). Oslo: Norges vassdrags- og energidirektorat (NVE). Available at: http://publikasjoner.nve.no/veileder/2015/veileder2015_07.pdf (accessed: 21.03.2018).

SVV. (2005) *Vegbygging.* (Håndbok 018). Statens vegvesen (SVV). Available at: https://brage.bibsys.no/xmlui/bitstream/handle/11250/189823/handbok_018_2005.pdf?sequence=1&isAllowed=y (accessed: 26.02.2018).

SVV. (2011) *Vegbygging.* (Håndbok 018). Statens vegvesen (SVV). Available at: https://brage.bibsys.no/xmlui/bitstream/handle/11250/195816/hb18.pdf?sequence=1&isAllowed=y (accessed: 26.02.2018).

SVV. (2014a) *Flom- og sørpeskred.* (Håndbok V139). Oslo: Statens vegvesen (SVV), Vegdirektoratet (VD). Available at: https://www.vegvesen.no/_attachment/740653/binary/1006021?fast_title=H%C3%A5ndbok+V139+Flom-+og+s%C3%B8rpeskred.pdf (accessed: 13.10.2017).

SVV. (2014b) *Standard for drift og vedlikehold av riksveger.* (Håndbok R610). Statens vegvesen (SVV). Available at: https://www.vegvesen.no/_attachment/61430/binary/964067 (accessed: 21.02.2018).

SVV. (2014c) *Vegbygging.* (Håndbok N200). Oslo: Statens vegvesen (SVV). Available at: https://www.vegvesen.no/_attachment/188382/binary/980128?fast_title=H%C3%A5ndbok+N200+Vegbygging+%2821+MB%29.pdf (accessed: 06.10.2017).

Tesaker, E. (2010). Kapittel 4: Vassdragshydraulikk. In Norges vassdrags- og energidirektorat (NVE) (ed.) *Vassdragshåndboka: håndbok i vassdragsteknikk*: Bokforslaget.

Tesaker, E. & Hoseth, K. A. (2010). Kapittel 10: Kulverter. In Norges vassdrags- og energidirektorat (NVE) (ed.) *Vassdragshåndboka: håndbok i vassdragsteknikk*: Bokforslaget.

Thordarson, S., Myrabø, S. & Flesjø, K. (2011) *Risiko- og sårbarhetsanalyser av stikkrenner mht værrelaterte hendelser.* (VD rapport 24). Statens vegvesen (SVV), Vegdirektoratet (VD). Available at: https://www.vegvesen.no/_attachment/218490/binary/426298 (accessed: 04.02.2018).

Time, B. (2016) *SFI Klima 2050 - Annual report 2015.* (Klima 2050 report 1-2016). Trondheim: SINTEF. Available at: https://brage.bibsys.no/xmlui/handle/11250/2388630 (accessed: 15.10.2017).

Trøstaker, J. (2016) *Isdannelse og kjøving i stikkrenner: Utfordringer og mulige løsninger for jernbane og annen infrastruktur*. Master's thesis. Trondheim: NTNU. Available at: https://brage.bibsys.no/xmlui/handle/11250/2449721 (accessed: 12.03.2018).

Tullis, B. P. (2012) *Hydraulic loss coefficients for culverts.* (NCHRP report 734). Washington D.C.: Transportation Research Board (TRB). Available at: http://www.trb.org/Main/Blurbs/168265.aspx (accessed: 20.03.2018).

Ugarelli, R. 2017. Infrastructure Asset Management (IAM), *TVM4141 Water and Wastewater Systems, Advanced Course*. Available at: https://ntnu.blackboard.com (accessed: 17.10.2017).

Vauclin, S. (2017) *Use of a parsimonious rainfall-runoff model for flood peak modelling in small ungauged catchments in Norway*. Trondheim: Norwegian University of Science and Technology.

Vesely, W. E., Goldberg, F. F., Roberts, N. H. & Haasl, D. F. (1981) *Fault tree handbook.* (NUREG-0492). Washington DC: US Nuclear Regulatory Commission. Available at: https://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr0492/ (accessed: 02.09.2017).

White, K. D. (1999) *Hydraulic and physical properties affecting ice jams.* (CRREL report 99-11). US Army Corps of Engineers. Available at: http://www.dtic.mil/dtic/tr/fulltext/u2/a375289.pdf (accessed: 01.04.2018).

Web service refrences

Banekart: http://banekart.banenor.no/kart/

Høydedata: https://hoydedata.no/LaserInnsyn/

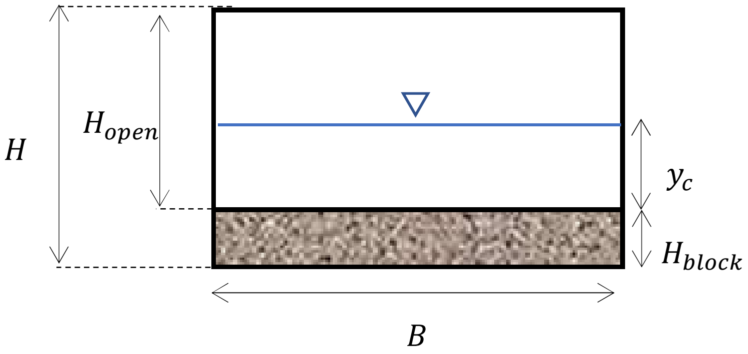
NVE Atlas: http://atlas.nve.no/

NVE Nevina: http://nevina.nve.no/

Vegkart: https://www.vegvesen.no/vegkart/vegkart/

Appendix A: Geometrical parameters

A.1 Geometrical parameters for box culverts



Open inlet or barrel height: $H_{open,i\ or\ b} = H - H_{block,i\ or\ b}$

Critical flow area: $A_c = B \cdot y_c$

Free surface width (critical): $T_c = B$

Inlet or barrel area: $A_{i\ or\ b} = B \cdot H_{open,i\ or\ b}$

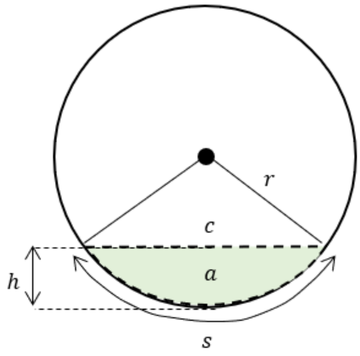
Wet bed perimeter (full): $P_{bed} = B$

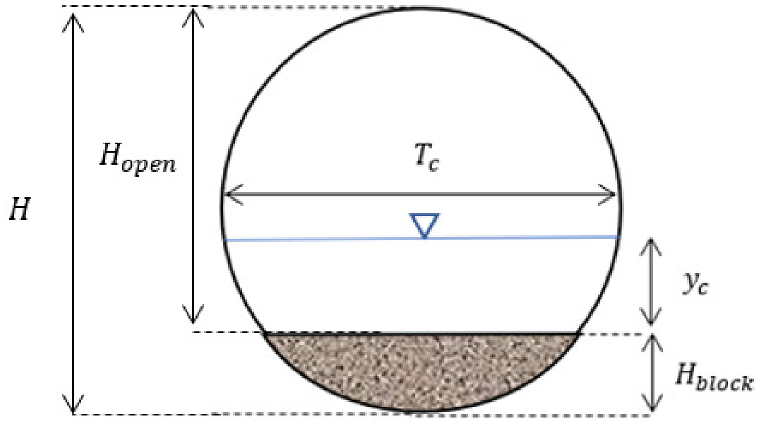
Wet culvert perimeter (full): $P_{culv} = B + 2\,H_{open,b}$

Total wet perimeter (full): $P = P_{culv} + P_{bed}$

Hydraulic radius (full): $R = \frac{A_b}{P}$

A.2 Geometrical parameters for pipe culverts





Area of segment: $a(h) = r^2 \cdot \cos^{-1}\left(\frac{r-h}{r}\right) - (r-h)\sqrt{2rh - h^2}$

Width of segment: $c(h) = 2\,r\sqrt{1 - \left(\frac{r-h}{r}\right)^2}$

Arc length of segment: $s(h,c) = \left(h + \frac{c^2}{4h}\right)\,\sin^{-1}\left(\frac{c}{h + c^2/4h}\right)$

Open inlet or barrel height: $H_{open,i\ or\ b} = H - H_{block,i\ or\ b}$

Critical flow area: $A_c = a\big(h = y_c + H_{block,i}\big) - a(h = H_{block,i})$

Free surface width (critical): $T_c\ = c(h = y_c + H_{block,i})$

Inlet or barrel area: $A_{i\ or\ b} = a(h = H_{open,i\ or\ b})$

Wet bed perimeter (full): $P_{bed} = c(h = H_{block,b})$

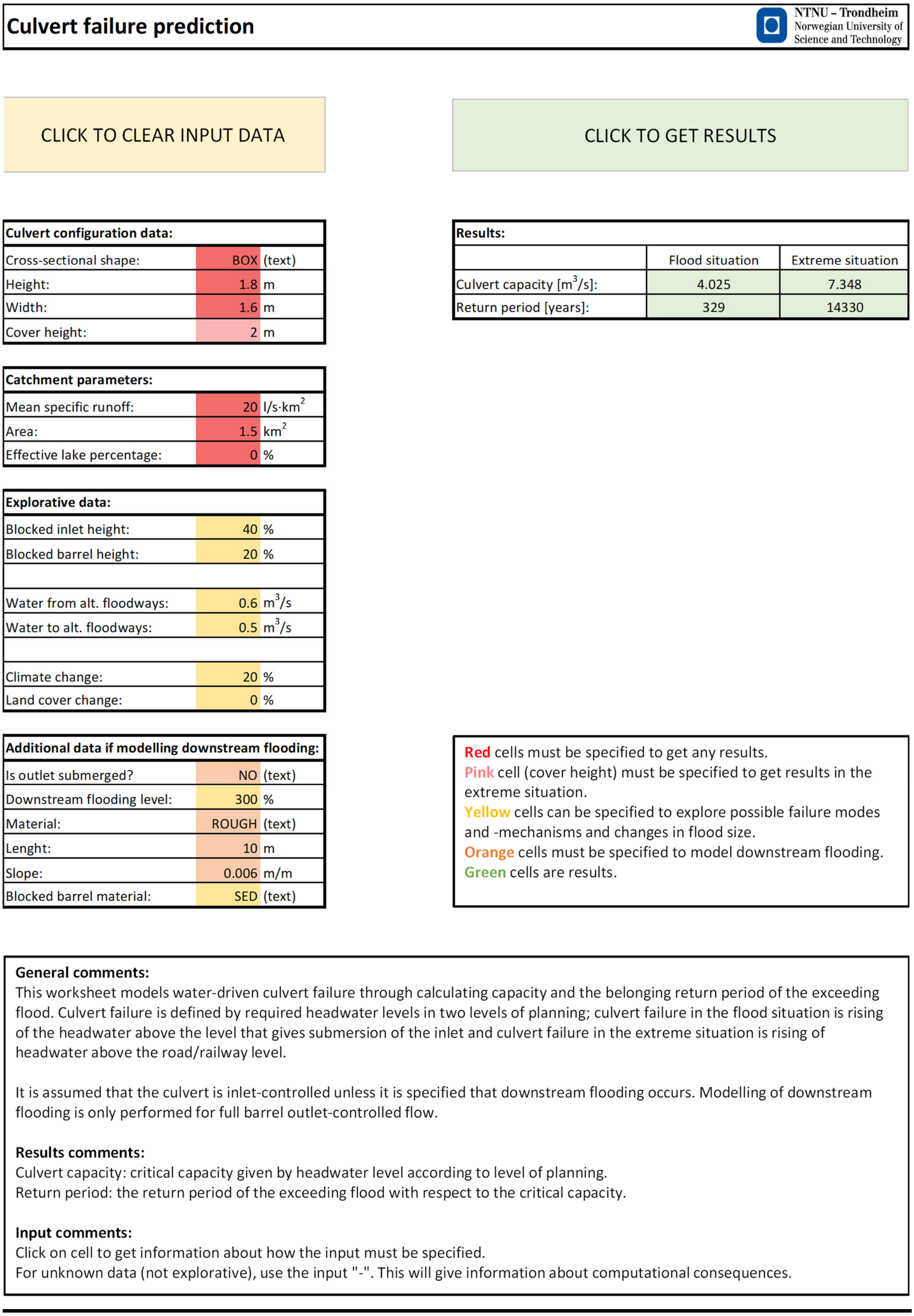
Wet culvert perimeter (full): $P_{culv} = s(h = H_{open,b}\ , c = P_{bed})$

Total wet perimeter (full): $P\ = P_{bed} + P_{culv}$

Hydraulic radius (full): $R = \frac{A_b}{P}$

Appendix B: Excel workbook “Culvert Failure Prediction”

B.1 Screenshot of worksheet “Inputs and Results”:’



Culvert failure prediction

NTNU – Trondheim
Norwegian University of
Science and Technology

Culvert configuration data:		
Cross-sectional shape:	BOX	(text)
Height:	1.8	m
Width:	1.6	m
Cover height:	2	m

Catchment parameters:		
Mean specific runoff:	20	$l/s{\cdot}km^2$
Area:	1.5	km^2
Effective lake percentage:	0	%

Explorative data:		
Blocked inlet height:	40	%
Blocked barrel height:	20	%
Water from alt. floodways:	0.6	m^3/s
Water to alt. floodways:	0.5	m^3/s
Climate change:	20	%
Land cover change:	0	%

Additional data if modelling downstream flooding:		
Is outlet submerged?	NO	(text)
Downstream flooding level:	300	%
Material:	ROUGH	(text)
Lenght:	10	m
Slope:	0.006	m/m
Blocked barrel material:	SED	(text)

Results:

	Flood situation	Extreme situation
Culvert capacity [m^3/s]:	4.025	7.348
Return period [years]:	329	14330

Red cells must be specified to get any results.
Pink cell (cover height) must be specified to get results in the extreme situation.
Yellow cells can be specified to explore possible failure modes and -mechanisms and changes in flood size.
Orange cells must be specified to model downstream flooding.
Green cells are results.

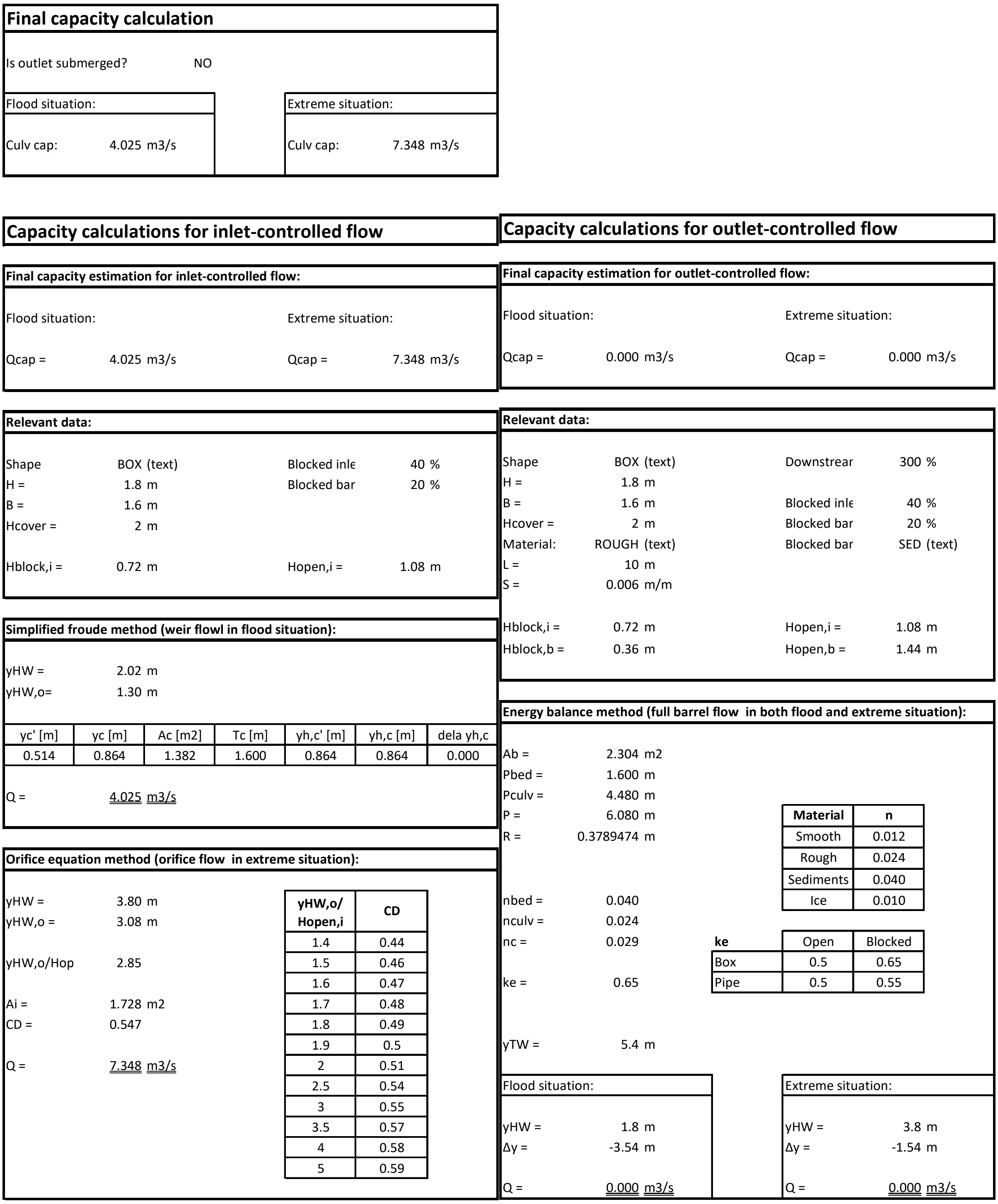
General comments:
This worksheet models water-driven culvert failure through calculating capacity and the belonging return period of the exceeding flood. Culvert failure is defined by required headwater levels in two levels of planning; culvert failure in the flood situation is rising of the headwater above the level that gives submersion of the inlet and culvert failure in the extreme situation is rising of headwater above the road/railway level.

It is assumed that the culvert is inlet-controlled unless it is specified that downstream flooding occurs. Modelling of downstream flooding is only performed for full barrel outlet-controlled flow.

Results comments:
Culvert capacity: critical capacity given by headwater level according to level of planning.
Return period: the return period of the exceeding flood with respect to the critical capacity.

Input comments:
Click on cell to get information about how the input must be specified.
For unknown data (not explorative), use the input "-". This will give information about computational consequences.

B.2 Screenshot of worksheet “CAPCALC”:



Final capacity calculation

Is outlet submerged? NO

Flood situation:

Culv cap: 4.025 m3/s

Extreme situation:

Culv cap: 7.348 m3/s

Capacity calculations for inlet-controlled flow

Final capacity estimation for inlet-controlled flow:

Flood situation:

Qcap = 4.025 m3/s

Extreme situation:

Qcap = 7.348 m3/s

Relevant data:

Shape BOX (text)
H = 1.8 m
B = 1.6 m
Hcover = 2 m

Hblock,i = 0.72 m

Blocked inle 40 %
Blocked bar 20 %

Hopen,i = 1.08 m

Simplified froude method (weir flowl in flood situation):

yHW = 2.02 m
yHW,o= 1.30 m

yc' [m]	yc [m]	Ac [m2]	Tc [m]	yh,c' [m]	yh,c [m]	dela yh,c
0.514	0.864	1.382	1.600	0.864	0.864	0.000

Q = 4.025 m3/s

Orifice equation method (orifice flow in extreme situation):

yHW = 3.80 m
yHW,o = 3.08 m

yHW,o/Hop 2.85

Ai = 1.728 m2
CD = 0.547

Q = 7.348 m3/s

yHW,o/ Hopen,i	CD
1.4	0.44
1.5	0.46
1.6	0.47
1.7	0.48
1.8	0.49
1.9	0.5
2	0.51
2.5	0.54
3	0.55
3.5	0.57
4	0.58
5	0.59

Capacity calculations for outlet-controlled flow

Final capacity estimation for outlet-controlled flow:

Flood situation:

Qcap = 0.000 m3/s

Extreme situation:

Qcap = 0.000 m3/s

Relevant data:

Shape BOX (text)
H = 1.8 m
B = 1.6 m
Hcover = 2 m
Material: ROUGH (text)
L = 10 m
S = 0.006 m/m

Downstrear 300 %

Blocked inle 40 %
Blocked bar 20 %
Blocked bar SED (text)

Hblock,i = 0.72 m
Hblock,b = 0.36 m

Hopen,i = 1.08 m
Hopen,b = 1.44 m

Energy balance method (full barrel flow in both flood and extreme situation):

Ab = 2.304 m2
Pbed = 1.600 m
Pculv = 4.480 m
P = 6.080 m
R = 0.3789474 m

nbed = 0.040
nculv = 0.024
nc = 0.029

ke = 0.65

yTW = 5.4 m

Material	n
Smooth	0.012
Rough	0.024
Sediments	0.040
Ice	0.010

ke	Open	Blocked
Box	0.5	0.65
Pipe	0.5	0.55

Flood situation:

yHW = 1.8 m
Δy = -3.54 m

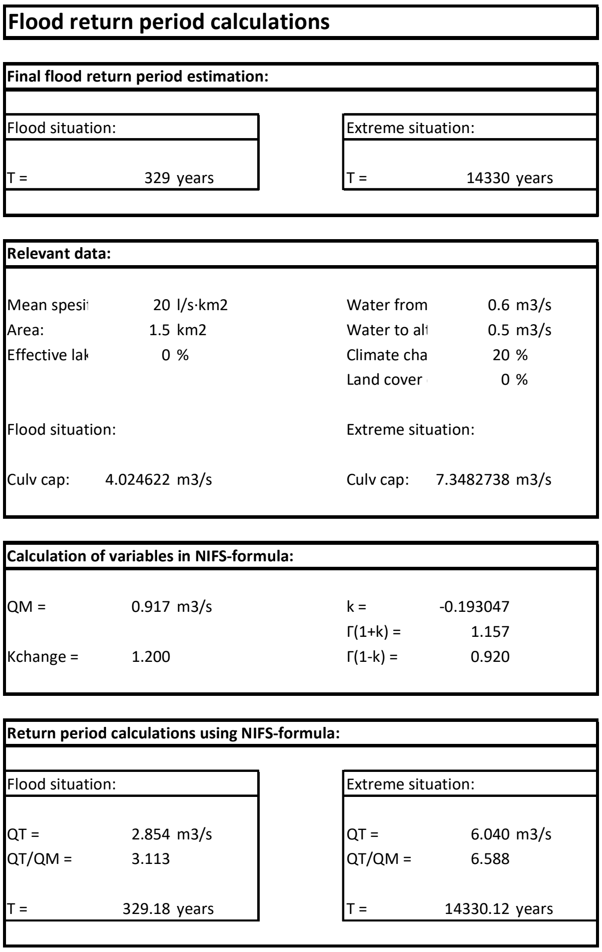
Q = 0.000 m3/s

Extreme situation:

yHW = 3.8 m
Δy = -1.54 m

Q = 0.000 m3/s

B.3 Screenshot of worksheet “RETURNCALC”:



Flood return period calculations

Final flood return period estimation:

Flood situation:			Extreme situation:		
T =	329	years	T =	14330	years

Relevant data:

Mean spesi	20	l/s·km2	Water from	0.6	m3/s
Area:	1.5	km2	Water to al	0.5	m3/s
Effective lak	0	%	Climate cha	20	%
			Land cover	0	%
Flood situation:			Extreme situation:		
Culv cap:	4.024622	m3/s	Culv cap:	7.3482738	m3/s

Calculation of variables in NIFS-formula:

QM =	0.917	m3/s	k =	-0.193047
			Γ(1+k) =	1.157
Kchange =	1.200		Γ(1-k) =	0.920

Return period calculations using NIFS-formula:

Flood situation:			Extreme situation:		
QT =	2.854	m3/s	QT =	6.040	m3/s
QT/QM =	3.113		QT/QM =	6.588	
T =	329.18	years	T =	14330.12	years

Appendix C: Results from tests on Excel workbook

C.1 Results from bug test

Bug test - output is returnperiod in years

Base case:

Response to variations in input data is found through keeping the other inputs equal to the ones provided in this base case.
Results are given for inlet-control first (outlet submerged = NO) and then for outlet-control (outlet submerged = YES).

Culvert configuration data:		
Cross-sectional shape:	box	(text)
Height:	1	m
Width:	1	m
Cover height:	2	m

Catchment parameters:		
Mean specific runoff:	20	l/s·km^2
Area:	1	km^2
Effective lake percentage:	0	%

Explorative data:		
Blocked inlet height:	0	%
Blocked barrel height:	0	%
Water from alt. floodways:	0	m^3/s
Water to alt. floodways:	0	m^3/s
Climate change:	0	%
Land cover change:	0	%

Additional data if modelling downstream flooding:		
Is outlet submerged?	NO/YES	(text)
Downstream flooding level:	100	%
Material:	rough	(text)
Lenght:	10	m
Slope:	0.005	m/m
Blocked barrel material:	-	(text)

Bug test for flood-calculation related inputs with inlet control:

Input variable:	**Mean specific runoff**						**Output result trend:**		**Corresponds?**
Input:	5	10	20	40	70	120	Expected:	Decrease due to larger runoff	YES
Flood output:	101909	7731	565	38	4	1	Actual:	Decrease	
Extreme output:	2507855	187503	13733	947	99	10			

Input variable:	**Area**						**Output result trend:**		**Corresponds?**
Input:	0.01	0.1	1	5	10	50	Expected:	Decrease due to more water being c	YES
Flood output:	4.21E+11	1.44E+07	565	2	1	1	Actual:	Decrease	
Extreme output:	1.11E+13	3.77E+08	13733	15	2	1			

Input variable:	**Effective lake percentage**						**Output result trend:**		**Corresponds?**
Input:	0	1	5	10	15	20	Expected:	Increase due to more dampening	YES
Flood output:	565	1743	4217	5364	5259	4680	Actual:	Increase	
Extreme output:	13733	39078	66814	59747	44502	31874			

Input variable:	**Water from alt. floodways**						**Output result trend:**		**Corresponds?**
Input:	0.00	0.10	1.00	2.00	3.00	5.00	Expected:	Decrease due to more incoming wat	YES
Flood output:	565	450	31	1	0	0	Actual:	Decrease until zero	
Extreme output:	13733	12158	3488	539	29	0			

Input variable:	**Water to alt. floodways**						**Output result trend:**		**Corresponds?**
Input:	0.00	0.10	1.00	2.00	3.00	5.00	Expected:	No change in flood and increase in e	YES
Flood output:	565	565	565	565	565	565	Actual:	No in flood, increase in extreme	
Extreme output:	13733	15469	40553	99263	212894	746152			

Input variable:	**Climate change**						**Output result trend:**		**Corresponds?**
Input:	0	10	20	40	70	100	Expected:	Increase due to increase in flood siz	YES
Flood output:	565	352	229	107	42	20	Actual:	Increase, same as for land cover cha	
Extreme output:	13733	8465	5447	2500	942	418			

Input variable:	**Land cover change**						**Output result trend:**		**Corresponds?**
Input:	0	10	20	40	70	100	Expected:	Increase due to increase in floodsize	YES
Flood output:	565	352	229	107	42	20	Actual:	Increase, same as for climate chang	
Extreme output:	13733	8465	5447	2500	942	418			

Bug test for capacity-calculation related inputs with inlet control:

Result type:	**Flood**	**Extreme**					Expected change:	Increase	**Corresponds?**
Output:	565	13733					Actual change:	Increase	YES

Input variable:	**Cross-sectional shape**						**Output result trend:**		**Corresponds?**
Input:	BOX	PIPE					Expected:	Decrease due to smaller area	YES
Flood output:	565	229					Actual:	Decrease	
Extreme output:	13733	4037							

Input variable:	**Height**						**Output result trend:**		**Corresponds?**
Input:	0.2	0.5	1.0	1.5	2.0	2.5	Expected:	Increase due to larger area	YES
Flood output:	1	4	565	12122	109390	607913	Actual:	Increase	
Extreme output:	6	377	13733	133227	672960	2334279			

Input variable:	**Width**						**Output result trend:**		**Corresponds?**
Input:	0.2	0.5	1.0	1.5	2.0	2.5	Expected:	Increase due to larger area	YES
Flood output:	1	20	565	4339	18669	58217	Actual:	Increase	
Extreme output:	6	418	13733	108556	473895	1490654			

Input variable:	**Cover height**						**Output result trend:**		**Corresponds?**
Input:	0.2 (0.2H)	0.5	1.0	2.0	3.0	5.0	Expected:	No change in flood and increase in e	YES
Flood output:	565	565	565	565	565	565	Actual:	None in flood and increase in extrer	
Extreme output:	565	968	3354	13733	37427	125348			

Input variable:	**Blocked inlet height**						**Output result trend:**		**Corresponds?**
Input:	0	10	20	40	70	100	Expected:	Decrease as inlet area decreases, sa	YES
Flood output:	565	258	108	14	1	0	Actual:	Decrease, same as blocked barrel	
Extreme output:	13733	8007	4458	976	32	0			

Input variable:	**Blocked barrel height**						**Output result trend:**		**Corresponds?**
Input:	0	10	20	40	70	100	Expected:	Decrease as inlet area decreases, sa	YES
Flood output:	565	258	108	14	1	0	Actual:	Decrease, same as blocked inlet	
Extreme output:	13733	8007	4458	976	32	0			

Bug test for capacity-calculation related inputs with outlet control:

Result type:	**Flood**	**Extreme**					Expected change:	Increse	**Corresponds?**
Output:	3	25005					Actual change:	Increase	YES

Input variable:	**Cross-sectional shape**						**Output result trend:**		**Corresponds?**
Input:	BOX	PIPE					Expected:	Decrease due to smaller area	YES
Flood output:	3	1					Actual:	Decrease	
Extreme output:	25005	4230							

Input variable:	**Height**						**Output result trend:**		**Corresponds?**
Input:	0.2	0.5	1.0	1.5	2.0	2.5	Expected:	Increase due to larger area same as	YES
Flood output:	1	1	3	19	74	220	Actual:	Increase	
Extreme output:	9	753	25005	198379	867592	2732030			

Input variable:	**Width**						**Output result trend:**		**Corresponds?**
Input:	0.2	0.5	1.0	1.5	2.0	2.5	Expected:	Increase due to larger area same as	YES
Flood output:	1	1	3	19	74	220	Actual:	Increase	
Extreme output:	9	753	25005	198379	867592	2732030			

Input variable:	**Cover height**						**Output result trend:**		**Corresponds?**
Input:	0	0.2	1.0	2.0	3.0	5.0	Expected:	No change in flood and increase in e	YES
Flood output:	3	3	3	3	3	3	Actual:	None in flood and increase in extrer	
Extreme output:	3	127	4577	25005	68877	250207			

Input variable:	**Material**						**Output result trend:**		**Corresponds?**
Input:	ROUGH	SMOOTH					Expected:	Increase due to less friction loss	YES
Flood output:	3	4					Actual:	Increase	
Extreme output:	25005	34598							

Input variable:	**Lenght**						**Output result trend:**		**Corresponds?**
Input:	1.0	5.0	10.0	20.0	40.0	80.0	Expected:	Increase or decrease depending of s	Depends on other variables
Flood output:	1	1	3	10	29	64	Actual:	Increase in flood, decrease in extrer	
Extreme output:	35075	29952	25005	18241	11069	5557			

Input variable:	Slope						Output result trend:		Corresponds?
Input:	0.0000	0.0001	0.0010	0.0050	0.0500	0.1000	Expected:	Increase due to larger level-differen	YES
Flood output:	0	1	1	3	708	4046	Actual:	Increase	
Extreme output:	23482	23512	23782	25005	41463	66030			

Input variable:	Downstream flooding level						Output result trend:		Corresponds?
Input:	100	110	140	200	300	310	Expected:	Decrease until Δy is zero	YES
Flood output:	3	0	0	0	0	0	Actual:	Decrease until Δy is zero	
Extreme output:	25005	22016	14396	4577	3	0			

Input variable:	Blocked inlet height						Output result trend:		Corresponds?
Input:	0	10	20	40	70	100	Expected:	Same decrease for all %, until comp	YES
Flood output:	3	3	3	3	3	0	Actual:	Same decrease for all %, until comp	
Extreme output:	25005	20362	20362	20362	20362	0			

Input variable:	Blocked barrel height with bed material sediments						Output result trend:		Corresponds?
Input:	0	10	20	40	70	100	Expected:	Decrease until completely blocked,	YES
Flood output:	3	1	1	1	1	0	Actual:	Decrease until completely blocked,	
Extreme output:	25005	4899	2430	424	6	0			

Input variable:	Blocked barrel height with bed material ice						Output result trend:		Corresponds?
Input:	0	10	20	40	70	100	Expected:	Decrease until completely blocked,	YES
Flood output:	3	2	1	1	1	0	Actual:	Decrease until completely blocked,	
Extreme output:	25005	8311	4375	898	19	0			

C.2 Results from test on design capacity

Comment: Charts are referenced to nomograms that shows the relationship between capacity, culvert diameter/height and headwater level and can be found in FHWA's *Hydraulic design of highway culverts*.

Test of design capacity calculations - output is capacity in m3/s

Inlet control:

Box culvert with inlet control

Nomogram: Chart 8A: Box culverts w/ headwall

yHW/D		**H (Height) = B (Width)**					
		0.3	0.6	0.9	1.5	2	2.5
1.2	*Q/Bnomo*	*0.25*	*0.75*	*1.5*	*3.5*	*5.7*	*8.2*
	Qnomo (B=	0.075	0.45	1.35	5.25	11.4	20.5
	Qoutput	0.110	0.625	1.722	6.176	12.678	22.147
	Δ Q	-0.035	-0.175	-0.372	-0.926	-1.278	-1.647
	Δ Q [%]	**-47**	**-39**	**-28**	**-18**	**-11**	**-8**
3	*Q/Bnomo*	*0.5*	*1.6*	*3.1*	*7.2*	*11.5*	*17*
	Qnomo (B =	0.15	0.96	2.79	10.8	23	42.5
	Hcover	*0.6*	*1.2*	*1.8*	*3*	*4*	*5*
	Qoutput	0.208	1.177	3.242	11.628	23.870	41.699
	Δ Q	-0.058	-0.217	-0.452	-0.828	-0.870	0.801
	Δ Q [%]	**-39**	**-23**	**-16**	**-8**	**-4**	**2**

Pipe culvert with inlet control

Nomogram: Chart 1A/2A: Concrete/CM pipe culvert w/ square edge headwall
Comment: Both charts gives same results

yHW/D		**H (Diameter)**					
		0.3	0.6	0.9	1.5	2	2.5
1.2	Qnomo	0.07	0.45	1.3	4.5	9	16
	Qoutput	0.092	0.521	1.435	5.148	10.567	18.460
	Δ Q	-0.022	-0.071	-0.135	-0.648	-1.567	-2.460
	Δ Q [%]	**-32**	**-16**	**-10**	**-14**	**-17**	**-15**
3	Qnomo	0.16	0.95	2.6	9.5	20	35
	Hcover	*0.6*	*1.2*	*1.8*	*3*	*4*	*5*
	Qoutput	0.163	0.924	2.547	9.133	18.747	32.750
	Δ Q	-0.003	0.026	0.053	0.367	1.253	2.250
	Δ Q [%]	**-2**	**3**	**2**	**4**	**6**	**6**

Outlet control:

Concrete box culvert with outlet control

Nomogram: Chart 15A: Concrete box culvert flowing full n = 0.012 w/ H = 2 m, L = 15 m and ke =
Comment: S = 0, L = 15 m, Material = smooth, Hcover = 2 used in calculations

Δy		**H (Height) = B (Width)**					
			0.6	0.9	1.5	2	2.5
2	Qnomo		1.65	4.2	11.5	20	32
	Qoutput		1.779	4.003	11.119	19.767	30.886
	Δ Q		-0.129	0.197	0.381	0.233	1.114
	Δ Q [%]		**-8**	**5**	**3**	**1**	**3**

Concrete pipe culvert with outlet control

Nomogram: Chart 5A: Concrete pipe flowing full n = 0.012 w/ H = 3m, L = 15 m and ke = 0.5
Comment: S = 0, L = 15 m, Material = smooth, Hcover = 2 used in calculations

Δy		**H (Diameter)**					
		0.3	0.6	0.9	1.5	2	2.5
2	Qnomo	0.27	1.25	3	9.2	16	25
	Qoutput	0.263	1.243	2.962	8.600	15.525	24.468
	Δ Q	0.007	0.007	0.038	0.600	0.475	0.532
	Δ Q [%]	**3**	**1**	**1**	**7**	**3**	**2**

Corrugated metal pipe culvert with outlet control

Nomogram: Chart 6A: CM pipe flowing full n = 0.024 w/ H = 2 m, L = 15 m and ke = 0.5
Comment: S = 0, L = 15 m, Material = rough, Hcover = 2 used in calculations

Δy		**H (Diameter)**					
		0.3	0.6	0.9	1.5	2	2.5
2	Qnomo	0.17	0.9	2.2	7.5	14	22
	Qoutput	0.169	0.930	2.408	7.590	14.176	22.810
	Δ Q	0.001	-0.030	-0.208	-0.090	-0.176	-0.810
	Δ Q [%]	**1**	**-3**	**-9**	**-1**	**-1**	**-4**

Appendix D: Results from case study

D.1 Results from inlet block- and accepted level analysis

Input for DP3:

Culvert configuration data:		
Cross-sectional shape:	BOX	(text)
Height:	1.8	m
Width:	1.2	m
Cover height:	11	m

Catchment parameters:		
Mean specific runoff:	19.6	$l/s \cdot km^2$
Area:	0.4	km^2
Effective lake percentage:	0	%

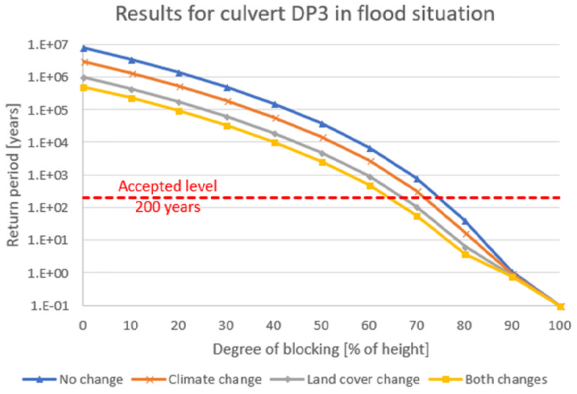
Explorative data:		
Blocked inlet height:		%
Blocked barrel height:		%
Water from alt. floodways:	0	m^3/s
Water to alt. floodways:	0	m^3/s
Climate change:		%
Land cover change:		%

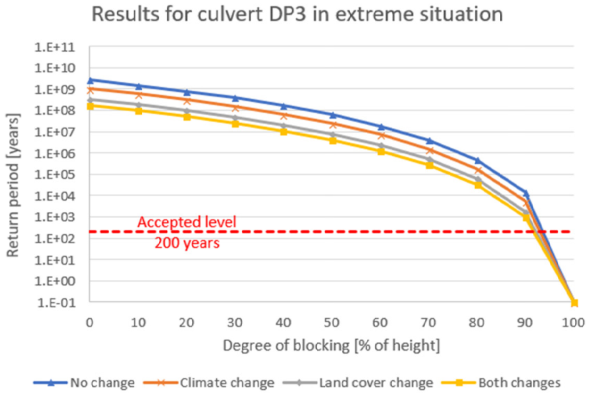
Additional data if modelling downstream flooding:		
Is outlet submerged?	NO	(text)
Downstream flooding level:		%
Material:		(text)
Lenght:		m
Slope:		m/m
Blocked barrel material:		(text)

Results for DP3:

Inlet block [%]	Return period [years]							
	No change		Climate change (+20%)		Land cover change (+50%)		Both changes	
	Flood	Extreme	Flood	Extreme	Flood	Extreme	Flood	Extreme
0	7794086	2724553022	3049011	1061587785	968257	335114111	509291	175566246
10	3454736	1523452383	1352832	593728221	430256	187487186	226535	98246676
20	1392665	798565462	546072	311309320	174017	98346749	91742	51550016
30	497964	385748607	195607	150433278	62503	47549772	33011	24933015
40	152291	167468669	59976	65340697	19238	20668254	10187	10842769
50	37673	62858027	14895	24541763	4806	7770827	2555	4079411
60	6875	19117630	2736	7471725	892	2369429	477	1245128
70	783	4173771	316	1633993	105	519484	57	273447
80	40	498953	17	195995	6	62626	4	33076
90	1	13892	1	5512	1	1788	1	954
100	0	0	0	0	0	0	0	0

Return period	Inlet block [%]							
	No change		Climate change (+20%)		Land cover change (+50%)		Both changes	
	Flood	Extreme	Flood	Extreme	Flood	Extreme	Flood	Extreme
200	75.0	95.7	71.8	94.8	67.3	93.5	64.4	92.7





Input for DP4:

Culvert configuration data:		
Cross-sectional shape:	PIPE	(text)
Height:	1.2	m
Width:	1.2	m
Cover height:	13	m

Catchment parameters:		
Mean specific runoff:	17.9	l/s·km^2
Area:	0.2	km^2
Effective lake percentage:	0	%

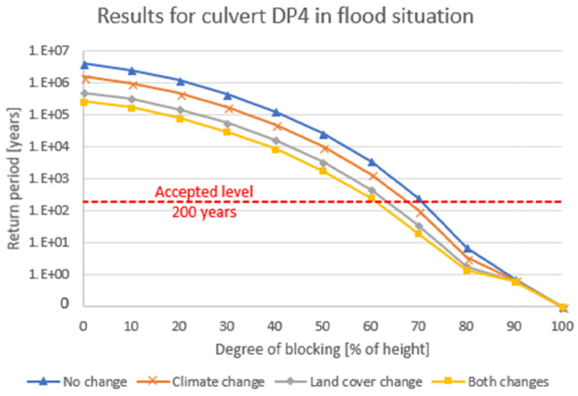
Explorative data:		
Blocked inlet height:		%
Blocked barrel height:		%
Water from alt. floodways:	0	m^3/s
Water to alt. floodways:	2.947	m^3/s
Climate change:		%
Land cover change:		%

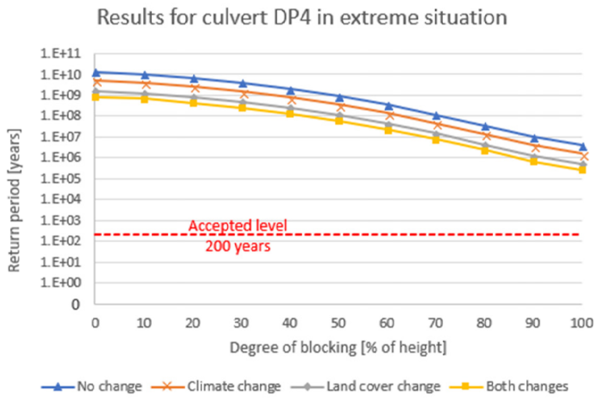
Additional data if modelling downstream flooding:		
Is outlet submerged?	NO	(text)
Downstream flooding level:		%
Material:		(text)
Lenght:		m
Slope:		m/m
Blocked barrel material:		(text)

Results for DP4:

Inlet block [%]	Return period [years]							
	No change		Climate change (+20%)		Land cover change (+50%)		Both changes	
	Flood	Extreme	Flood	Extreme	Flood	Extreme	Flood	Extreme
0	4098101	13165589167	1605429	5127934524	510908	1617863049	269109	847289548
10	2598943	10413376568	1018819	4056249756	324552	1279883236	171065	670334140
20	1222453	6863320534	479817	2673781916	153135	843838723	80815	442016956
30	451015	3965996115	177372	1545356181	56775	487852870	30020	255595264
40	128064	2023865083	50520	788814093	16245	249120776	8616	130554080
50	26389	908054132	10464	354050569	3391	111877045	1808	58651831
60	3532	354829656	1414	138419120	465	43772892	250	22959786
70	250	119817629	102	46774563	35	14807693	20	7772519
80	7	35380446	3	13825842	2	4383558	1	2303237
90	1	9997328	1	3911926	1	1242771	1	653851
100	0	4100516	0	1606374	0	511207	0	269267

Return period	Inlet block [%] (no extra floodway)							
	No change		Climate change (+20%)		Land cover change (+50%)		Both changes	
	Flood	Extreme	Flood	Extreme	Flood	Extreme	Flood	Extreme
200	70.7	91.8	67.7	90.7	63.6	89.2	61.3	88.3


Results for culvert DP4 in flood situation


Results for culvert DP4 in extreme situation

Input for DP5:

Culvert configuration data:		
Cross-sectional shape:	PIPE	(text)
Height:	1	m
Width:	1	m
Cover height:	16	m

Catchment parameters:		
Mean specific runoff:	17.9	l/s·km^2
Area:	0.1432	km^2
Effective lake percentage:	0	%

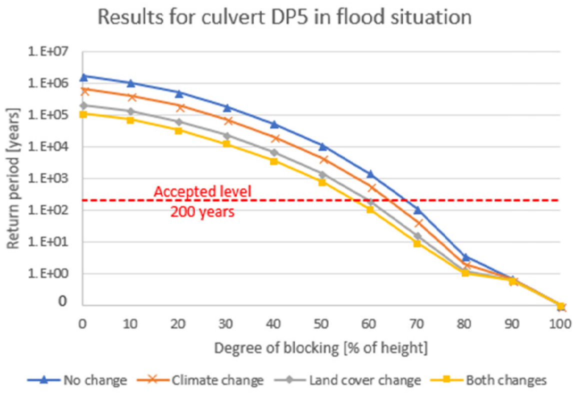
Explorative data:		
Blocked inlet height:		%
Blocked barrel height:		%
Water from alt. floodways:	0	m^3/s
Water to alt. floodways:	1.868	m^3/s
Climate change:		%
Land cover change:		%

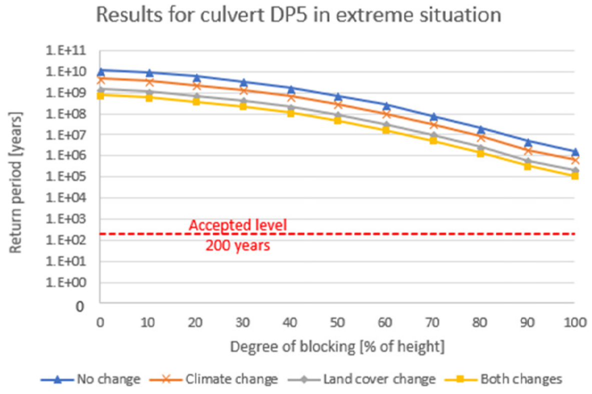
Additional data if modelling downstream flooding:		
Is outlet submerged?	NO	(text)
Downstream flooding level:		%
Material:		(text)
Lenght:		m
Slope:		m/m
Blocked barrel material:		(text)

Results for DP5:

Inlet block [%]	Return period [years]							
	No change		Climate change (+20%)		Land cover change (+50%)		Both changes	
	Flood	Extreme	Flood	Extreme	Flood	Extreme	Flood	Extreme
0	1735429	11790970927	680750	4592679254	217068	1449061932	114485	758911954
10	1101251	9296343753	432326	3621268862	138017	1142693184	72850	598502656
20	518580	6059570624	203883	2360760816	65232	745097472	34482	390311164
30	191668	3436524790	75529	1339119742	24249	422780632	12848	221514724
40	54576	1704457022	21585	664372255	6968	209843353	3705	109978547
50	11299	733306291	4496	285947378	1465	90371699	784	47382728
60	1525	269391690	614	105107487	204	33247009	111	17441677
70	110	83024034	46	32420093	16	10267712	9	5390997
80	4	21421550	2	8375140	1	2657332	1	1396914
90	1	5019067	1	1965666	1	625286	1	329264
100	0	1735420	0	680747	0	217066	0	114485

Return period	Inlet block [%] (no extra floodway)							
	No change		Climate change (+20%)		Land cover change (+50%)		Both changes	
	Flood	Extreme	Flood	Extreme	Flood	Extreme	Flood	Extreme
200	68.0	92.0	64.7	90.9	60.1	89.4	57.2	88.5


Results for culvert DP5 in flood situation


Results for culvert DP5 in extreme situation

Input for DP6:

Culvert configuration data:		
Cross-sectional shape:	BOX	(text)
Height:	0.6	m
Width:	0.6	m
Cover height:	8	m

Catchment parameters:		
Mean specific runoff:	17.9	l/s·km^2
Area:	0.0626	km^2
Effective lake percentage:	0	%

Explorative data:		
Blocked inlet height:		%
Blocked barrel height:		%
Water from alt. floodways:	0	m^3/s
Water to alt. floodways:	0	m^3/s
Climate change:		%
Land cover change:		%

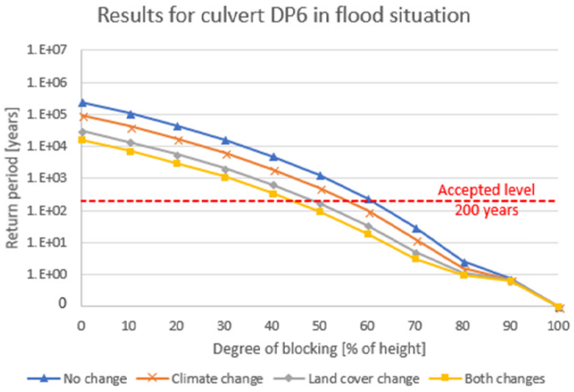
Additional data if modelling downstream flooding:		
Is outlet submerged?	NO	(text)
Downstream flooding level:		%
Material:		(text)
Lenght:		m
Slope:		m/m
Blocked barrel material:		(text)

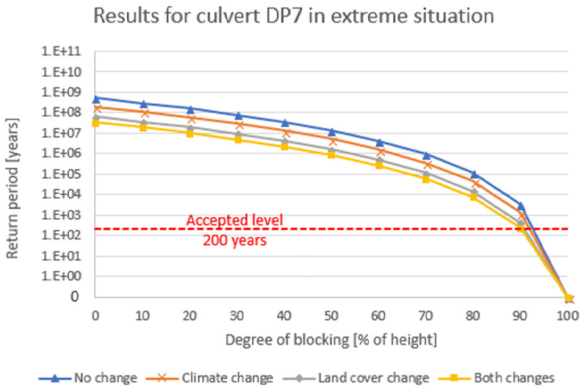
Results for DP6:

(Comment: values in *italic* are for above the maximum degree of blocking)

Inlet block [%]	Return period [years]							
	No change		Climate change (+20%)		Land cover change (+50%)		Both changes	
	Flood	Extreme	Flood	Extreme	Flood	Extreme	Flood	Extreme
0	247265	515947442	97377	201227848	31233	63614646	16538	33360029
10	110228	294049455	43502	114721843	13998	36285199	7427	19034502
20	44771	157185510	17719	61350352	5725	19416379	3047	10189632
30	16174	77477528	6426	30255898	2088	9583082	1116	5031811
40	5020	34346232	2005	13422067	657	4255715	353	2236127
50	1270	13175370	512	5153839	170	1636530	93	860743
60	241	4100378	99	1606320	34	511190	19	269258
70	30	917856	13	360451	5	115129	3	60789
80	3	112985	2	44587	1	14345	1	7611
90	*1*	*3290*	*1*	*1318*	*1*	*434*	*1*	*234*
100	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*

Return period	Inlet block [%]							
	No change		Climate change (+20%)		Land cover change (+50%)		Both changes	
	Flood	Extreme	Flood	Extreme	Flood	Extreme	Flood	Extreme
200	61.0	*94.3*	56.0	*93.2*	48.9	*91.5*	44.5	*90.3*





Input for DP7:

Culvert configuration data:		
Cross-sectional shape:	BOX	(text)
Height:	0.8	m
Width:	0.6	m
Cover height:	7	m

Catchment parameters:		
Mean specific runoff:	17.9	$l/s{\cdot}km^2$
Area:	0.14	km^2
Effective lake percentage:	0	%

Explorative data:		
Blocked inlet height:		%
Blocked barrel height:		%
Water from alt. floodways:	0	m^3/s
Water to alt. floodways:	0	m^3/s
Climate change:		%
Land cover change:		%

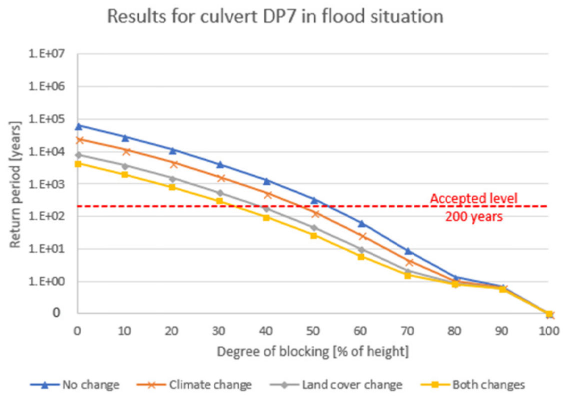
Additional data if modelling downstream flooding:		
Is outlet submerged?	NO	(text)
Downstream flooding level:		%
Material:		(text)
Lenght:		m
Slope:		m/m
Blocked barrel material:		(text)

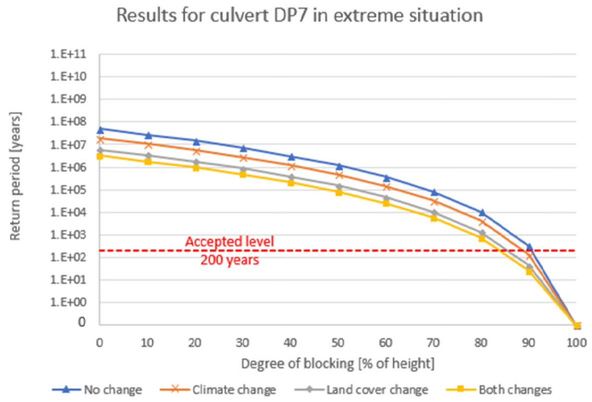
Results for DP7:

(Comment: values in *italic* are for above the maximum degree of blocking)

Inlet block [%]	Return period [years]							
	No change		Climate change (+20%)		Land cover change (+50%)		Both changes	
	Flood	Extreme	Flood	Extreme	Flood	Extreme	Flood	Extreme
0	64229	48878759	25389	19095095	8189	6051562	4352	3178728
10	28725	27646851	11386	10806275	3688	3427394	1966	1801265
20	11716	14668687	4661	5737297	1518	1821473	812	957901
30	4257	7177864	1702	2809819	559	893188	301	470117
40	1333	3160104	537	1238435	178	394338	97	207786
50	342	1204719	140	472868	48	150923	26	79649
60	67	373094	28	146789	10	47015	6	24870
70	9	83338	4	32917	2	10605	2	5632
80	1	10310	1	4104	1	1338	1	716
90	*1*	*311*	*1*	*127*	*1*	*43*	*1*	*24*
100	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*

Return period	Inlet block [%]							
	No change		Climate change (+20%)		Land cover change (+50%)		Both changes	
	Flood	Extreme	Flood	Extreme	Flood	Extreme	Flood	Extreme
200	53.5	*90.9*	47.5	*89.0*	37.6	*86.3*	33.7	*84.5*





Input for DP8:

Culvert configuration data:		
Cross-sectional shape:	BOX	(text)
Height:	0.9	m
Width:	0.6	m
Cover height:	4	m

Catchment parameters:		
Mean specific runoff:	17.9	$l/s{\cdot}km^2$
Area:	0.1108	km^2
Effective lake percentage:	0	%

Explorative data:		
Blocked inlet height:		%
Blocked barrel height:		%
Water from alt. floodways:	0	m^3/s
Water to alt. floodways:	0	m^3/s
Climate change:		%
Land cover change:		%

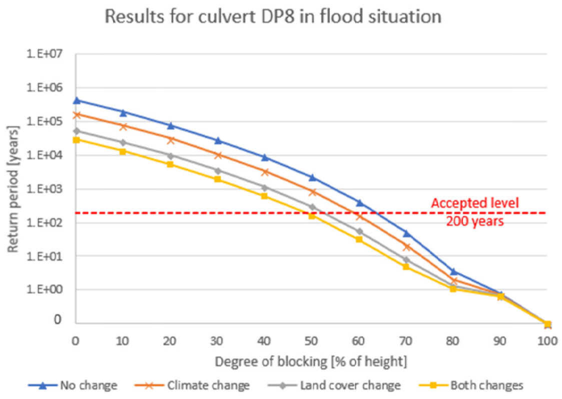
Additional data if modelling downstream flooding:		
Is outlet submerged?	NO	(text)
Downstream flooding level:		%
Material:		(text)
Lenght:		m
Slope:		m/m
Blocked barrel material:		(text)

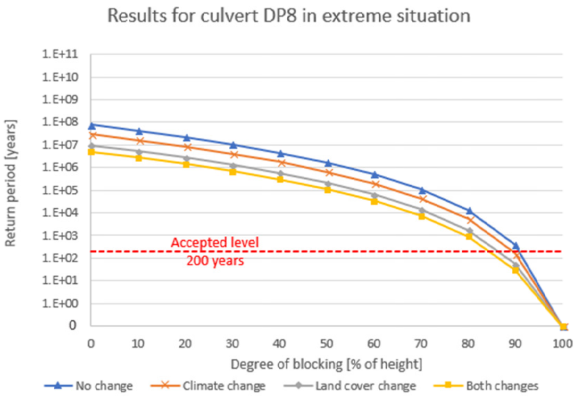
Results for DP8:

(Comment: values in *italic* are for above the maximum degree of blocking)

Inlet block [%]	**Return period [years]**							
	No change		**Climate change (+20%)**		**Land cover change (+50%)**		**Both changes**	
	Flood	Extreme	Flood	Extreme	Flood	Extreme	Flood	Extreme
0	445302	76738377	175130	29967481	56060	9491839	29643	4983940
10	198282	42484226	78129	16599054	25080	5261502	13287	2764072
20	80413	22048462	31765	8619988	10235	2734899	5436	1437647
30	28990	10545939	11491	4126335	3722	1310763	1983	689579
40	8970	4534935	3573	1776307	1166	565168	625	297648
50	2259	1687265	907	661888	300	211068	162	111326
60	425	509504	173	200322	59	64096	32	33883
70	52	110848	22	43746	8	14076	5	7469
80	4	13336	2	5303	1	1726	1	923
90	*1*	*390*	*1*	*159*	*1*	*54*	*1*	*30*
100	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*

Return period	**Inlet block [%]**							
	No change		**Climate change (+20%)**		**Land cover change (+50%)**		**Both changes**	
	Flood	Extreme	Flood	Extreme	Flood	Extreme	Flood	Extreme
200	63.9	*91.3*	59.2	*89.5*	52.7	*86.9*	48.5	*85.2*





Input for DP9:

Culvert configuration data:		
Cross-sectional shape:	PIPE	(text)
Height:	0.6	m
Width:	0.6	m
Cover height:	4	m

Catchment parameters:		
Mean specific runoff:	17.9	l/s·km^2
Area:	0.0659	km^2
Effective lake percentage:	0	%

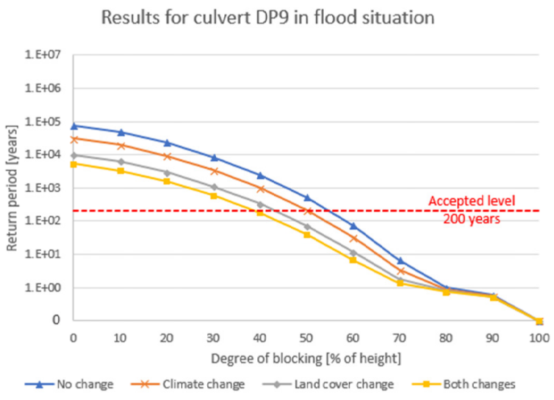
Explorative data:		
Blocked inlet height:		%
Blocked barrel height:		%
Water from alt. floodways:	0	m^3/s
Water to alt. floodways:	0	m^3/s
Climate change:		%
Land cover change:		%

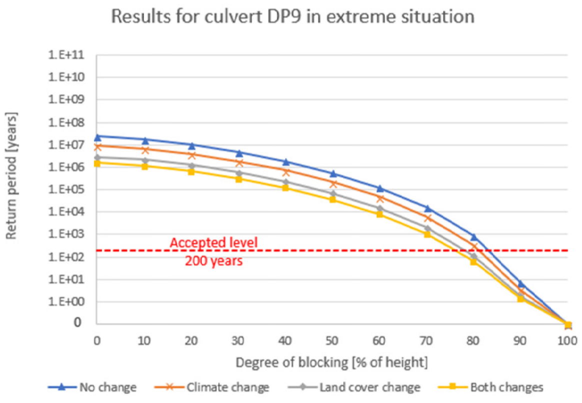
Additional data if modelling downstream flooding:		
Is outlet submerged?	NO	(text)
Downstream flooding level:		%
Material:		(text)
Lenght:		m
Slope:		m/m
Blocked barrel material:		(text)

Results for DP9:

Inlet block [%]	Return period [years]							
	No change		Climate change (+20%)		Land cover change (+50%)		Both changes	
	Flood	Extreme	Flood	Extreme	Flood	Extreme	Flood	Extreme
0	77721	23474713	30704	9177008	9895	2911350	5256	1530305
10	49541	17230337	19600	6738046	6330	2138631	3367	1124497
20	23444	9940085	9300	3889553	3016	1235676	1609	650122
30	8749	4738905	3485	1856089	1138	590498	609	310970
40	2529	1842861	1015	722821	335	230448	181	121531
50	537	559065	218	219765	74	70297	40	37154
60	77	121265	32	47845	12	15389	7	8163
70	7	15866	3	6304	2	2049	1	1095
80	1	858	1	347	1	116	1	63
90	1	7	1	4	1	2	1	1
100	0	0	0	0	0	0	0	0

Return period	Inlet block [%]							
	No change		Climate change (+20%)		Land cover change (+50%)		Both changes	
	Flood	Extreme	Flood	Extreme	Flood	Extreme	Flood	Extreme
200	55.4	83.7	50.5	81.5	43.6	78.4	39.3	76.4





Input for DP10 (not downstream flood):

Culvert configuration data:		
Cross-sectional shape:	PIPE	(text)
Height:	2	m
Width:	2	m
Cover height:	13	m

Catchment parameters:		
Mean specific runoff:	17.9	l/s·km^2
Area:	2.19	km^2
Effective lake percentage:	0	%

Explorative data:		
Blocked inlet height:		%
Blocked barrel height:		%
Water from alt. floodways:	0	m^3/s
Water to alt. floodways:	0	m^3/s
Climate change:		%
Land cover change:		%

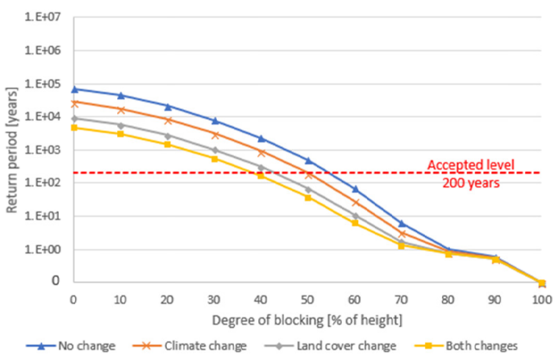
Additional data if modelling downstream flooding:		
Is outlet submerged?	NO	(text)
Downstream flooding level:		%
Material:		(text)
Lenght:		m
Slope:		m/m
Blocked barrel material:		(text)

Results for DP10 (not downstream flood):

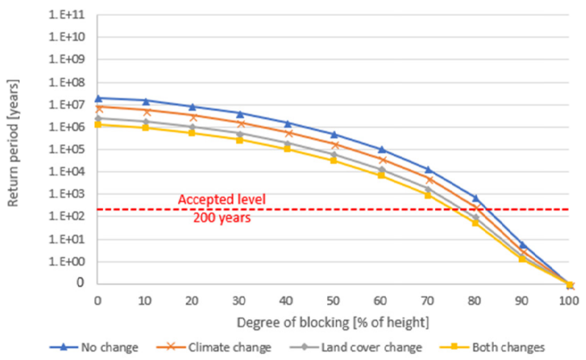
Inlet block [%]	Return period [years]							
	No change		Climate change (+20%)		Land cover change (+50%)		Both changes	
	Flood	Extreme	Flood	Extreme	Flood	Extreme	Flood	Extreme
0	71226	20310157	28146	7941057	9074	2519810	4821	1324693
10	45352	14896974	17948	5826487	5799	1849742	3086	972751
20	21479	8588074	8523	3361104	2765	1068074	1476	562041
30	8018	4091634	3196	1602899	1044	510104	559	268687
40	2319	1590177	931	623864	307	198972	166	104957
50	494	482159	201	189593	68	60674	37	32077
60	71	104550	30	41267	11	13282	6	7048
70	6	13681	3	5439	2	1770	1	946
80	1	741	1	300	1	101	1	55
90	1	6	1	3	1	2	1	1
100	0	0	0	0	0	0	0	0

Return period	Inlet block [%]							
	No change		Climate change (+20%)		Land cover change (+50%)		Both changes	
	Flood	Extreme	Flood	Extreme	Flood	Extreme	Flood	Extreme
200	54.9	83.3	50.0	81.1	43.1	77.9	38.6	75.9

Results for culvert DP10 in flood situation



Results for culvert DP10 in extreme situation



D.2 Results from downstream flood analysis

Input for DP10 for downstream flood:

Culvert configuration data:		
Cross-sectional shape:	PIPE	(text)
Height:	2	m
Width:	2	m
Cover height:	13	m

Catchment parameters:		
Mean specific runoff:	17.9	$l/s{\cdot}km^2$
Area:	2.19	km^2
Effective lake percentage:	0	%

Explorative data:		
Blocked inlet height:		%
Blocked barrel height:		%
Water from alt. floodways:	0	m^3/s
Water to alt. floodways:	0	m^3/s
Climate change:		%
Land cover change:		%

Additional data if modelling downstream flooding:		
Is outlet submerged?	YES	(text)
Downstream flooding level:		%
Material:	SMOOTH	(text)
Lenght:	80	m
Slope:	0.17	m/m
Blocked barrel material:		(text)

Results for DP10 when modelling with downstream flood:

(Comment: values in *italic* are for above the maximum degree of blocking and values in **bold** are equal to the results for inlet control

Failure return period for increasing downstream flood level (no blocking):

Downstream level [%]	**Return period [years]**							
	No change		**Climate change (+20%)**		**Land cover change (+50%)**		**Both changes**	
	Flood	Extreme	Flood	Extreme	Flood	Extreme	Flood	Extreme
100	**71226**	**20310157**	**28146**	**7941057**	**9074**	**2519810**	**4821**	**1324693**
400	**71226**	**20310157**	**28146**	**7941057**	**9074**	**2519810**	**4821**	**1324693**

Failure return period for increasing barrel block, for 100% and 400% downstream flood level (no change in flood):

Barrel block [%]	**Blocking by sediments - return period [years]**				**Blocking by ice - return period [years]**			
	100%		**400%**		**100%**		**400%**	
	Flood	Extreme	Flood	Extreme	Flood	Extreme	Flood	Extreme
0	**71226**	**20310157**	**71226**	**20310157**	**71226**	**20310157**	**71226**	**20310157**
10	**45352**	**14896974**	**45352**	**14896974**	**45352**	**14896974**	**45352**	**14896974**
20	**21479**	**8588074**	**21479**	**8588074**	**21479**	**8588074**	**21479**	**8588074**
30	**8018**	**4091634**	**8018**	3738420	**8018**	**4091634**	**8018**	**4091634**
40	**2319**	**1590177**	**2319**	955398	**2319**	**1590177**	**2319**	**1590177**
50	**494**	339821	**494**	176693	**494**	**482159**	**494**	**482159**
60	***71***	*34156*	***71***	*17840*	**71**	**104550**	**71**	**104550**
70	***6***	*1628*	***6***	*859*	**6**	**13681**	**6**	13004
80	***1***	*22*	***1***	*13*	**1**	302	**1**	161
90	***1***	*1*	***1***	*1*	***1***	*1*	***1***	*1*
100	***0***	*0*	***0***	*0*	***0***	*0*	***0***	*0*