REPORT

GeoRisk Assessment and Management (GRAM)

SUBPROJECT 4.3: CLIMATE ADAPTATION IN RISK AND VULNERABILITY ANALYSIS

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Foreword

The present report is a contribution to two R&D projects at NGI:

20140003 – GeoRisk Assessment and Management (GRAM)
20150145 – Klima 2050, WP3 Landslides triggered by hydro-meteorological processes

NGI, the Research Council of Norway, and the Klima 2050 consortium are all greatly thanked for the financial support.

Summary

All Norwegian municipalities are legally required to incorporate the impact of climate change (climate adaptation) in their mandatory risk and vulnerability analyses, assessing all possible events. This report presents a framework on how the regional climate prognoses can be applied to analyse the impact of natural hazards on a local level, or in simplified terms: "what will be the implications of a 20% increase in frequency and intensity of extreme precipaption events in terms of e.g. landslides and flooding in my valley"? The influence of climate change on hydro-meteorological hazards in Norway is mainly related to an expected increase in annual precipitation as well as an increase in frequency and intensity of heavy rainfall (with subsequent surface water and flooding/erosion problems). In coastal areas, sea level rise and higher storm surges constitute a future threat to low-lying areas. How severe the changes finally will be, is critically dependent on the future amount of global greenhouse gas emissions.

At the same time, urbabnisation leads to a larger number of human-valued assets that can be exposed to hazards. The changes in both climatic and societal factors increase the total exposure. In 2011, the year with the so far highest registered pay-out after disasters by the Norwegian Natural Perils Pool, the payments for losses alone amounted to 2,605 billion NOK

To assist the Norwegian municipalities with climate adaptation in risk and vulnerability analysis, one should first list possible site-specific indicators (e.g., localisation and health status of important infrastructure, localisation of settlements, work force characteristics – e.g., mostly communiting out/in of municipality?, demography, etc.) to identify the relevant natural hazards. Secondly, a GIS database is seen as a valuable first-order assessment tool to obtain an overview of the multi-hazard situation in certain cities, villages, valleys, etc., both under the current and under a changing climate (not the least because most municipalities already work with GIS systems to map and manage their municipial assets). The next step will be to compile the meteorological base data for the site/region. Future expected precipitation changes for the different climatic regions in Norway (see example for region Østlandet in Table 0.1) together with the precipitation normals give the baseline for the precipitation to be expected in the future.

Table 0.1: Expected increase in precipitation per season (in %) for region Østlandet with the RCP8.5 scenario. Scenario "medium" = median value from several regional climate models; the scenarios "low" (10 percentile) and "high" (90 percentile) indicates the spread between low and high climate projections (https://klimaservicesenter.no).

2045	Season			
Scenario	DJF	MAM	JJA	SON
low	2.5	2.0	-5.0	-4.8
medium	16.1	16.2	3.2	4.8
high	29.0	20.0	15.5	17.5

2065	Season			
Scenario	DJF	MAM	JJA	SON
low	10.0	7.0	-7.5	-5.5
medium	16.7	21.5	2.1	7.4
high	27.0	31.0	20.0	16.5

Risk-based analysis provides a suitable and efficient conceptual standpoint for investigating adaptation to climate change, as it includes the events that affect human-valued assets, the way in which such assets are impacted to the events themselves, and the ways in which communities are able to reduce such impacts. Recommended approaches for climate adaptation on a municipality level are described for urban and river flooding, for storm surge and sea level rise, and for landslides including clay, debris and rock slides. For each of these hazards, the present report illustrates how a (first-order) hazard, vulnerability and risk analysis can be performed for climate adaptation. An example of storm surge/sea level rise hazard analysis for a future climate in the city of Larvik is shown in Figure 0.1. Possible risk reduction measures are also litsed for each type of hazard. Each section concludes with new ideas on how the specific hazard can be implemented into a framework for multi-hazard assessment, in terms of frequency-intensity relationships of input parameters, relevant hazard interactions, definition of reference return periods, typical uncertainties, etc. A general framework for multi-hazard assessment based on Bayesian networks is recommended.

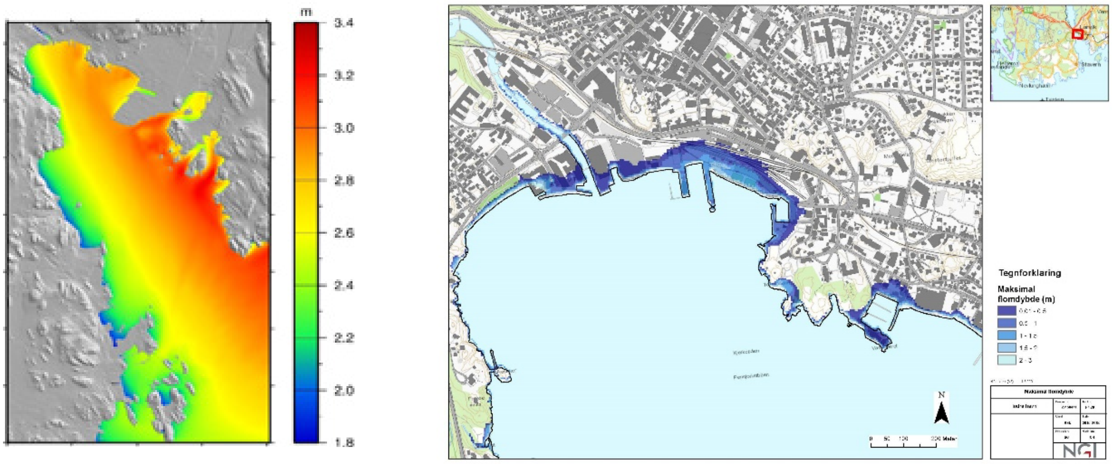

Figure 0-1: Example for numerical modelling in Larvik, showing maximum values for combined effects of wind surge, waves, 200-year storm surge level, sea- level rise (2065) and climate add-on (NGI, 2016a).

Multi-risk extends the concept of multi-hazard analysis by incorporating the temporal variability of vulnerability and exposure. Multi-risk estimation allows a more complete and realistic risk assessment, and provides useful indications and criteria for decision-making in the risk management process. An approach comprising a three-level framework is recommended. The third level is a detailed quantitative multi-risk analysis based on Bayesian networks, allowing a quantitative assessment of the effects of the interaction between different threats. This is achieved by estimating the probability of triggering/cascade effects and by modelling the time-variant vulnerability of a system exposed to multiple threats. An example Bayesian network for the Level 3 analysis is shown in Figure 0-2.

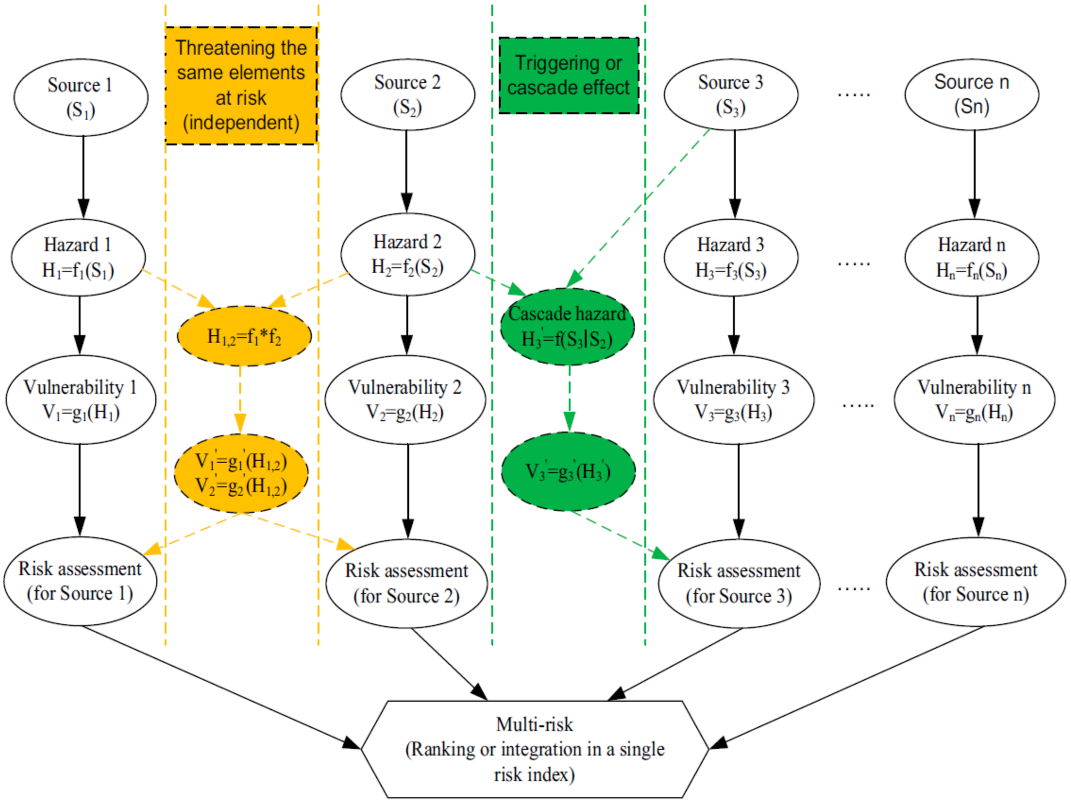

Figure 0-2: Example Bayesian network for the Level 3 multi-risk analysis (Liu et al. 2015).

The multi-risk framework assumes that risk estimation has been performed for single threats. However, it may not be immediate to identify which of the threats are prioritary in terms of hazard and of the possible impact on the area and human-valued assets of interest. In order to assess preliminarily which single-threat risk estimation efforts should be pursued prior to the multi-risk estimation process, it is useful to adopt e.g. the analytic hierarchy process (AHP). This process is a comprehensive and rational structured technique, based on mathematics and subjective assessment, that can be used effectively to rank threats which are concurrent in a given (common) area. It can be seen as a tool for the prioritization of single-threats risk estimation studies for subsequent multi-risk investigations using the three-level framework.

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1 Introduction

The Norwegian Civil protection law (Sivilbeskyttelsesloven; https://lovdata.no/dokument/NL/lov/2010-06-25-45) states that the municipalities have the overall responsibility to ensure the safety of their inhabitants. The authorities emphasized the responsibility further after release of the report "Climate in Norway 2100" (Hanssen-Bauer et al., 2015), designed to provide a scientific basis for climate adaptation in Norway. This implies that all municipalities must incorporate the impact of climate change (climate adaptation) in their mandatory risk and vulnerability analyses, assessing all possible related threats (DSB, 2014; NGI, 2015).

This report is a contribution to the NGI SP6 Project 20140003 GRAM (GeoRisk Assessment and Management), subproject 4.3 "Climate adaptation in risk and vulnerability analysis" and to Work Package 3 "Landslides triggered by hydro-meteorological processes" of the Centre for Research-based Innovation (SFI) project Klima 2050, http://www.klima2050.no/ (NGI project 20150145). The idea is to present a framework on how the regional climate prognoses can be applied to analyse the impacts of natural hazards on a local level, or in simplified terms: "what will be the implications of a 20% increase in frequency and intensity of extreme precipitation events in terms of landslides and flooding in my valley"?

After more general sections on climate prognoses (Section 2), description of the reference risk-based approach and terminology for studies of climate adaptation (Section 3) and analysis of natural hazards under a changing climate in Norway (Section 4), the framework is elaborated further. Approaches for selected hazards like flooding, storm surges and sea level rise, as well as lanslides are recommended (Section 0). Supporting examples and experience are gathered from a pilot project on climate change adaptation in Larvik and Lardal municipalities (NGI, 2016a). Finally, a framework for probabilistic multi-hazard and multi-risk assessment is presented (Section 6; see also NGI, 2016b), that provides an effective tool for political decisions in risk management. Including the concept of multi-hazard brings us a step beyond what is described in the GRAM strategy and framework for risk management (NGI, 2016c).

2 Climate prognoses

Figure 2-1: Rain water drain in Larvik, exceeding its capacity during a precipitiation event on June 29, 2012 (Østlands-Posten, photographer: Franck Løreng).

Projections of future climate change depend on the assumptions made concerning the most probable future emission scenarios. Emission scenarios describe various scenarios for the future development of global emissions of greenhouse gases and aerosols (particles). The development of these emissions are largely dependent on world population growth, technological development, private sector development, and the political framework.

It has to be kept in mind that climate projections are uncertain for several reasons. There is uncertainty associated with at least: (1) future anthropogenic emissions; (2) natural climate variations; and (3) climate models. The first type of uncertainty is to some extent addressed by considering several emission scenarios. The second type of uncertainty is partly due to internal climate variability and partly due to variations in natural forcings. Internal variations can be simulated by climate models, and the use of different models provides an estimate of this uncertainty through the observed scatter among the models' outputs. Variations in natural climate forcing are, however, not taken into account, but unless they are larger than they have been for the last 100 years they will have relatively little impact. The third type of uncertainty, which is associated with climate model errors and simplifications, is to a certain extent handled by using several models, because different models display different errors and are based on different simplifications. Processes we do not know, and that therefore no models are able to describe, can however not be covered (Hanssen-Bauer et al, 2015).

In September 2015, the updated edition of the report "Climate in Norway 2100" (Hanssen-Bauer et al., 2015) was released. This report is designed to provide a scientific basis for climate adaptation in Norway, and includes both atmospheric climate, hydrology, permafrost, landslides and ocean climate. The calculations are based on climate developments in Norway so far, and on assumptions about future greenhouse gas emissions. With continued rapidly increasing greenhouse gas emissions, the following climate change are expected in Norway towards the end of this century (cf. Hanssen-Bauer et al., 2015):

- Annual temperature: Increase by approximately 4.5 °C (span: 3.3 to 6.4 °C)
- Annual precipitation: Increase by approximately 18% (span: 7 to 23%)
- Torrential rain episodes will become more powerful and will occur more frequently (Figure 2-1)
- Rain floods will become larger and more frequent
- Snow melt floods will become smaller and less frequent
- In low-lying areas, snow will be almost gone for many years, while some high mountain areas may experience higher amounts of snow
- There will be fewer glaciers, and those remaining will be much smaller
- Sea level will increase by between 15 and 55 cm, depending on the locality

For Norway, there are two changes that will create the greatest challenges for society: changes in precipitation (with subsequent surface water and flooding problems) and sea level rise. How severe the changes finally will be, is critically dependent on the future amount of global greenhouse gas emissions. With reduced greenhouse gas emissions, climate change will be significantly less. Therefore, CO_2 reduction and climate adaptation are important. In climate change research, emissions are usually converted to additional radiative forcing to the atmosphere. The number linked to each representative concentration pathways refers to estimated additional radiative forcing in the year 2100 compared to pre-industrial times (year ~1765), e.g. the RCP4.5 scenario (Figure 2-2) corresponds to an additioal radioative forcing of 4.5 W/m^2 to the atmosphere (Hanssen-Bauer et al., 2015). The RCP8.5 scenario represents large greenhouse gas emissions and is often called the "business as usual" scenario because the rate of increase of greenhouse gas emissions follows the observations of the recent decades. The scenario implies that CO_2-emission will be three times higher in 2100 than it is today, in addition to a high increase in metan emissions.

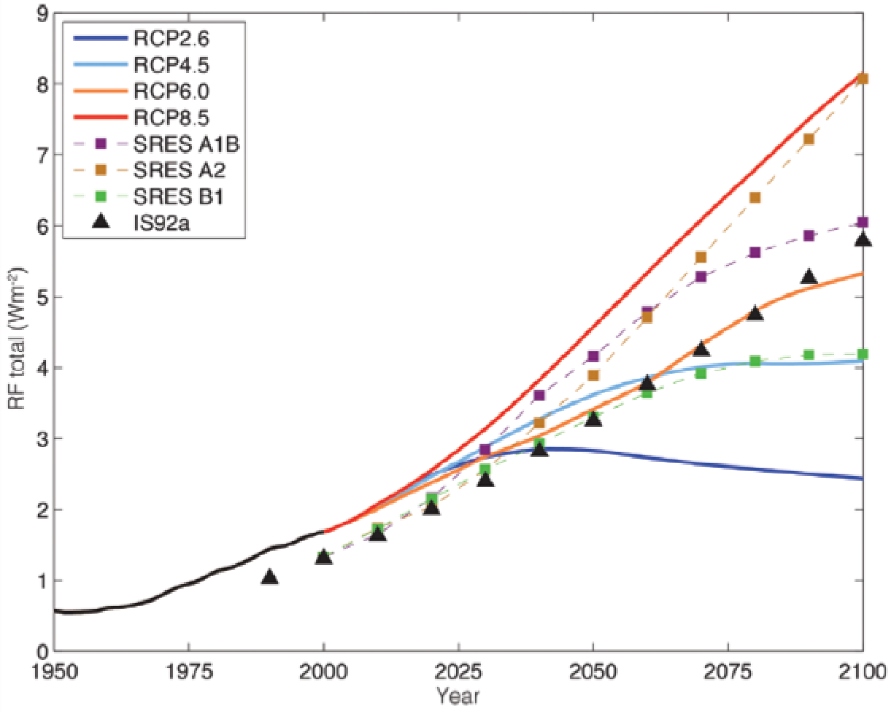


Figure 2-2: Additional radiative forcing [W/m^2] from 1950 to 2100 compared to pre-industrial times. Scenarios from previous IPCC reports (IS92a, SRES A1B, A2 og B1) presented ogether with the new Representative Concentration Pathways (RCPs) (From IPCC, 2013; reproduced by Hanssen-Bauer et al., 2015).

3 Risk-based approach to climate adaptation studies

Risk-based analysis provides a suitable and efficient conceptual standpoint for investigating adaptation to climate change, as it includes the events that affect human-valued assets, the way in which such assets are impacted to the events themselves, and the ways in which communities are able to reduce such impacts.

Risk is a widely used concept in many disciplines, ranging from technical to social sciences. The literature shows a considerable heterogeneity in terms of glossary and operational risk-based approaches, be they qualitative or quantitative. A best-practice risk-based approach to the study of human-valued systems thus requires and relies on the preliminary definition of a reference glossary as to avoid conceptual and operational misinterpretations, lack of clarity, and miscommunication in outputs. This report refers to – and aims to avoid any discrepancy with - the ISO (2009a) Risk management – principles and guidelines and the ISO (2009b) Risk Management Vocabulary. The first document provides principles and generic guidelines on risk management. It aims to promote the harmonization of risk management processes in existing and future standards, and to provide a common approach in support of standards dealing with specific risks and/or sectors while not replacing those standards. Importantly, it recognizes that "the design and implementation of risk management plans and frameworks will need to take into account the varying needs of a specific organization, its particular objectives, context, structure, operations, processes, functions, projects, products, services, or assets and specific practices employed." The second document aims to provide a basic vocabulary to develop common understanding on risk management concepts and terms among organizations and functions. For an outline of basic risk theory and a general framework relevant for risk management related projects at NGI, see NGI (2016c).

Figure 3-1 (ISO 2009a) illustrates in flowchart format the relationships between the risk management principles, framework, and process. Concerning the risk management process, Table 3-1 reports a set of selected entries adapted from the ISO (2009b) Risk Management Vocabulary.

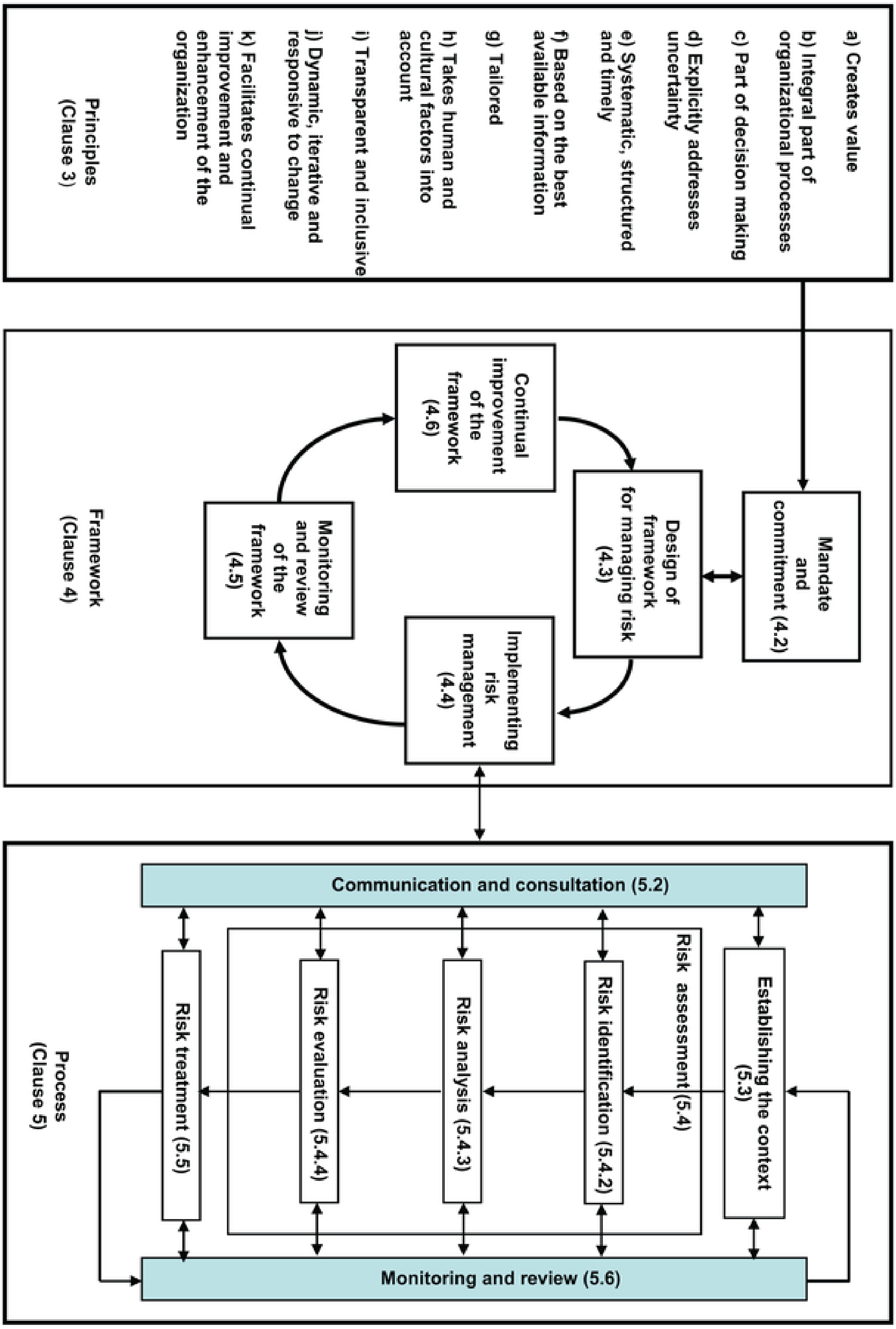


Figure 3-1: Relationships between the risk management principles, framework, and process (from ISO 2009a)

Table 3-1: Entries related to the risk management process, selected and adapted from the ISO (2009b) Risk Management Vocabulary.

Term	**Explanation**
Communication and consultation	Continual and iterative processes that an organization conducts to provide, share or obtain information and to engage in dialogue with stakeholders regarding the management of risk.
Consequence	Outcome of an event affecting objectives. An event can lead to a range of consequences. A consequence can be certain or uncertain and can have positive or negative effects. Consequnce can be expressed qualitatively or quantitetively.
Exposure	Extent to which an organization, stakeholder and/or vulnerable asset is subject to an event
Hazard	Source of potential harm. Hazard can be a risk source.
Likelihood	Chance of something happening, whether defined, measured or determined objectively or subjectively, qualitatively or quantitatively, and described using general terms or mathematically, for instance as a probability or a frequency over a given time period.
Monitoring	Continual checking, supervising, critically observing or determining the status in order to identify change from the performance level required or expected. Monitoring can be applied to a risk management framework, risk management process, risk or control.
Residual risk	Risk remaining after risk treatment. Residual risk can contain unidentified risk.
Risk	Effect of uncertainty on objectives. An effect is a deviation from the expected - positive and/or negative. Objectives can have different aspects (such as financial, health and safety, and environmental goals) and can apply at different levels (such as strategic, organization-wide, project, product and process). Uncertainty is the state, even partial, of deficiency of information related to, understanding or knowledge of, an event, its consequence, or likelihood.
Risk analysis	Process to comprehend the nature of risk (2.1) and to determine the level of risk . Risk analysis provides the basis for risk evaluation and decisions about risk treatment, and includes risk estimation.
Risk assessment	Overall process of risk identification, risk analysis and risk evaluation.
Risk criteria	Terms of reference against which the significance of a risk is evaluated. Risk criteria can be derived from standards, laws, policies and other requirements.
Risk description	Structured statement of risk usually containing four elements: sources, events, causes and consequences.
Risk evaluation	Process of comparing the results of risk analysis with risk criteria to determine whether the level of risk is acceptable or tolerable. Risk evaluation assists in the decision about risk treatment.
Risk identification	Process of finding, recognizing and describing risks. Risk identification involves the identification of risk sources, events, their causes and their potential consequences. Risk identification can involve historical

Term	**Explanation**
	data, theoretical analysis, informed and expert opinions, and stakeholder's needs.
Level of risk	Magnitude of a risk or combination of risks, expressed in terms of the combination of consequences and their likelihood.
Risk management	Coordinated activities to direct and control an organization with regard to risk. A risk management framework comprise a set of components that provide the foundations and organizational arrangements for designing, implementing, monitoring, reviewing and continually improving the risk management process. The foundations include the policy, objectives, mandate and commitment to manage risk. The organizational arrangements include plans, relationships, accountabilities, resources, processes and activities.
Risk source	Tangible or intangible element which alone or in combination has the intrinsic potential to give rise to risk.
Risk treatment	Process to modify risk. Risk treatment can involve: (a) avoiding the risk by deciding not to start or continue with the activity that gives rise to the risk; (b) taking or increasing risk in order to pursue an opportunity; (c) removing the risk source; (d) changing the likelihood or hazard; (e) changing the consequences; (f) sharing the risk with another party or parties (including contracts and risk financing); and (g) retaining the risk by informed decision. Risk treatments that deal with negative consequences are sometimes referred to as “risk mitigation”, “risk elimination”, “risk prevention” and “risk reduction”. Risk treatment can create new risks or modify existing risks.
Vulnerability	Intrinsic properties of something resulting in susceptibility to a risk source that can lead to an event with a consequence.

In the present report, as is encountered in common practice, the term "hazard" is used interchangeably as a synonym to "event" and to "likelihood".

The comprehensive character of risk is highlighted by the general risk model

$$R = H \cdot C \tag{3.1}$$

which can be implemented both qualitatively and quantitively, and which sees risk as the output of the interaction between hazard H (in its likelihood declination) and consequence C. Consequence can be modeled and defined as the product of the combination of the vulnerability V and the exposure E of the assets themselves to the aforementioned hazardous event:

$$C = V \cdot E \tag{3.2}$$

4 Natural hazard analysis in a changing climate

Society is exposed to both natural and human-induced hazards. Observed changes in climate have led to more severe climate impacts, for instance extreme precipitation events leading to flooding and erosion. In many areas, urbanisation increases, causing, for instance increased housing and commuter infrastructure needs. This, in turn, leads to a larger number of human-valued assets that can be exposed to hazards. The changes in both societal and climatic factors increase the total exposure. In 2011, the year with the so far highest registered pay-out after disasters by the Norwegian Natural Perils Pool, the payments for losses alone amounted to 2,605 billion NOK (Figure 4-1).

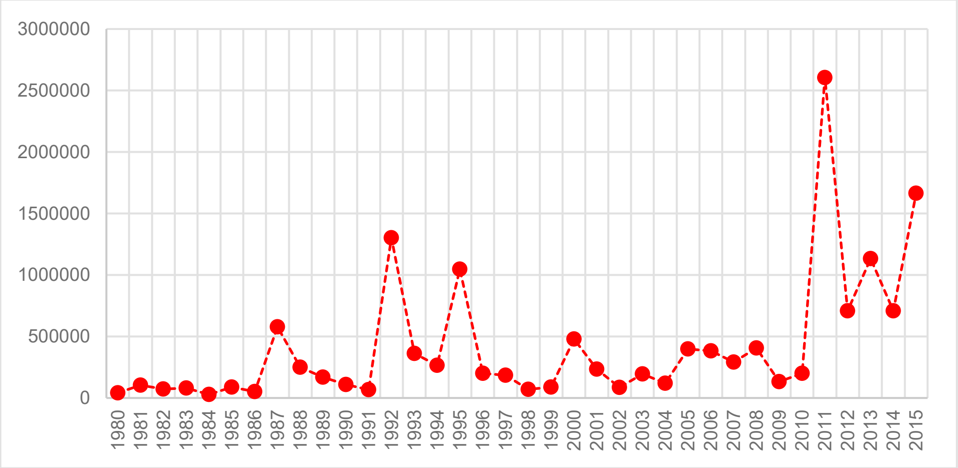


Figure 4-1: Loss payments (in 1000 NOK) by the Norwegian Natural Perils Pool between 1980 and 2015. Figure compiled from data on http://www.naturskade.no/no/

Annual climate data in Norway since the year 1900 clearly demonstrate an increase in frequency and intensity of extreme weather events (e.g., Hanssen-Bauer et al., 2015; Dyrrdal et al., 2012; NCCS, 2016; NGI, 2013a; Vikhamar-Schuler et al., 2016). The combined effect of the changing climate and other important changes, such as changes in demography and land use, result in a highly dynamic risk system, which is not sufficiently treated using current methods for risk management in Norway.

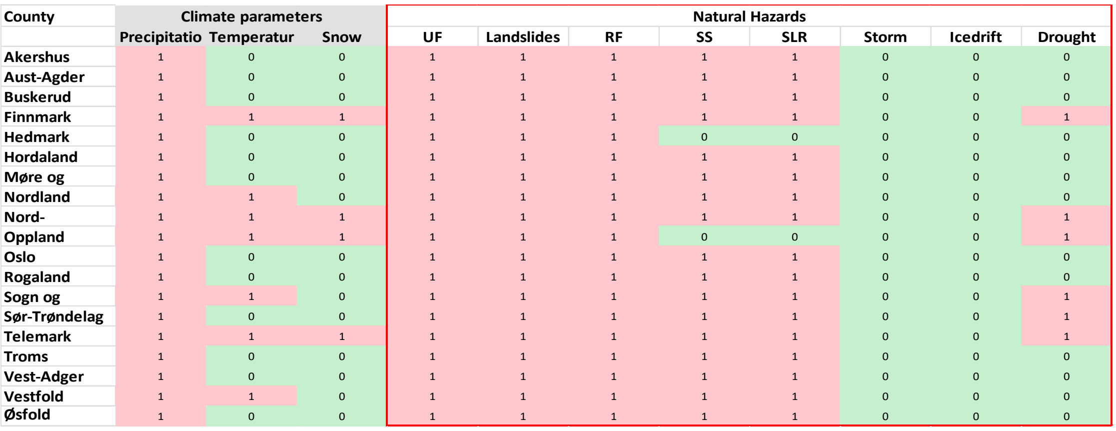
The influence of climate change on hydro-meteorological hazards in Norway is mainly related to an expected increase in annual precipitation as well as an increase in frequency and intensity of heavy rainfall (cf. Hanssen-Bauer et al., 2015; and Section 2 of this report). In coastal areas, sea level rise and higher storm surges constitute a future threat to low-lying areas (cf. DSB, 2016). Natural hazards that have to be expected to occur with present or increased frequencies and magnitudes under a future climate include:

- Urban flooding
- River flooding (floods caused by rainfall or by snowmelt)
- Landslides (rock falls, large rock failures, soil slides, quick clay slides, debris flows, slush flows, snow avalanches)

- Coastal floods (storm surges, sea level rise, erosion)
- Storms
- Icedrift
- Droughts

The "Norsk klimaservicesenter" (https://klimaservicesenter.no/) is summarizing expected climatic changes for each Norwegian county and describes the expected threats each county will have to deal with in the future. So far, ten full county reports are available, while short descriptions are already available for all counties on http://www.klimatilpasning.no/fylkesoversikt/. Table 4-1 summarizes the hazard profile of each county according to the overview given on Klimatilpasning.no.

Table 4-1: Hazard profiles for Norwegian counties, according to reports on www.klimatilpasning.no. UF = Urban flooding; RF = River flooding; SS = Storm surges; SLR = Sea level rise. A value of 0 means that there are no additional threats to be expected in the most probable future climate scenario, whereas a value of 1 means that the threat potential in the most probable future climate scenario will be increased.



County	Climate parameters			Natural Hazards							
	Precipitatio	Temperatur	Snow	UF	Landslides	RF	SS	SLR	Storm	Icedrift	Drought
Akershus	1	0	0	1	1	1	1	1	0	0	0
Aust-Agder	1	0	0	1	1	1	1	1	0	0	0
Buskerud	1	0	0	1	1	1	1	1	0	0	0
Finnmark	1	1	1	1	1	1	1	1	0	0	1
Hedmark	1	0	0	1	1	1	0	0	0	0	0
Hordaland	1	0	0	1	1	1	1	1	0	0	0
Møre og	1	0	0	1	1	1	1	1	0	0	0
Nordland	1	1	0	1	1	1	1	1	0	0	0
Nord-	1	1	1	1	1	1	1	1	0	0	1
Oppland	1	1	1	1	1	1	0	0	0	0	1
Oslo	1	0	0	1	1	1	1	1	0	0	0
Rogaland	1	0	0	1	1	1	1	1	0	0	0
Sogn og	1	1	0	1	1	1	1	1	0	0	1
Sør-Trøndelag	1	0	0	1	1	1	1	1	0	0	1
Telemark	1	1	1	1	1	1	1	1	0	0	1
Troms	1	0	0	1	1	1	1	1	0	0	0
Vest-Adger	1	0	0	1	1	1	1	1	0	0	0
Vestfold	1	1	0	1	1	1	1	1	0	0	0
Øsfold	1	0	0	1	1	1	1	1	0	0	0

This information gives a coarse overview of the general future susceptibility to hydro-meteorological hazards of each county (see also Figure 4-2 left). However, the Norwegian Civil protection law (Sivilbeskyttelsesloven; https://lovdata.no/dokument/NL/lov/2010-06-25-45) states that the municipalities have the overall responsibility to ensure the safety of their inhabitants. Hence, the management of the impact of climate change (climate adaptation) must be handled at the municipality level. All municipalities are required to carry out risk and vulnerability analyses, assessing all possible events (DSB, 2014; NGI, 2015; Eidsvig et al., 2016). Many municipalities still need to implement this requirement. Furthermore, the analyses performed today represent the situation at the time of assessment only, and are thus static. Some are probably already outdated because of climate change and/or development activities in the municipality, or inadequate because they do not consider cascading effects of multi-hazards.

To assist the Norwegian municipalities with climate adaptation in risk and vulnerability analysis, one should first embark on a risk identification and description effort. This would include listing possible site-specific indicators (e.g., localisation and health status of important infrastructure, localisation of settlements, work force characteristics – e.g., mostly commuting out/in of municipality?, demography, etc.) to identify the relevant natural hazards (see also NGI, 2015; Eidsvig et al., 2016). Secondly, a GIS database is seen as a valuable first-order assessment tool to obtain an overview of the multi-hazard situation in certain cities, villages, valleys, etc., both under the current and under a changing climate (not the least because most municipalities already work with GIS systems to map and manage their municipial assets). Such a first-order identification and description will depend on the climatic, topographic, demographical, socio-economic, and environmental setting of the study area in question, but a database could contain the following elements:

1. County overview: based on the climate profiles developed by the Norsk klimaservicesenter. (www.klimatilpasning.no/fylkesoversikt), cf. Figure 4-2 left
2. Municipality level: spatial distribution of:
    a. hazard zones
    b. low-lying coastal areas
    c. rivers
    d. landslide areas
3. Such data can be harvested from literature, existing databases (e.g. from Norwegian Meteorological Institute/MET, www.kartverket.no/sehavniva), local knowledge, terrain analysis, remote sensing, etc.
4. Climate information, 1 x 1 km seNorge rasters with historical and future climate data (from MET)
5. Thematic maps (e.g. on infrastructure and buildings) for exposure and vulnerability analysis.

A preliminary example for a map including storm surge risk on municipality level for the county of Rogaland is shown in Figure 4-2 right.

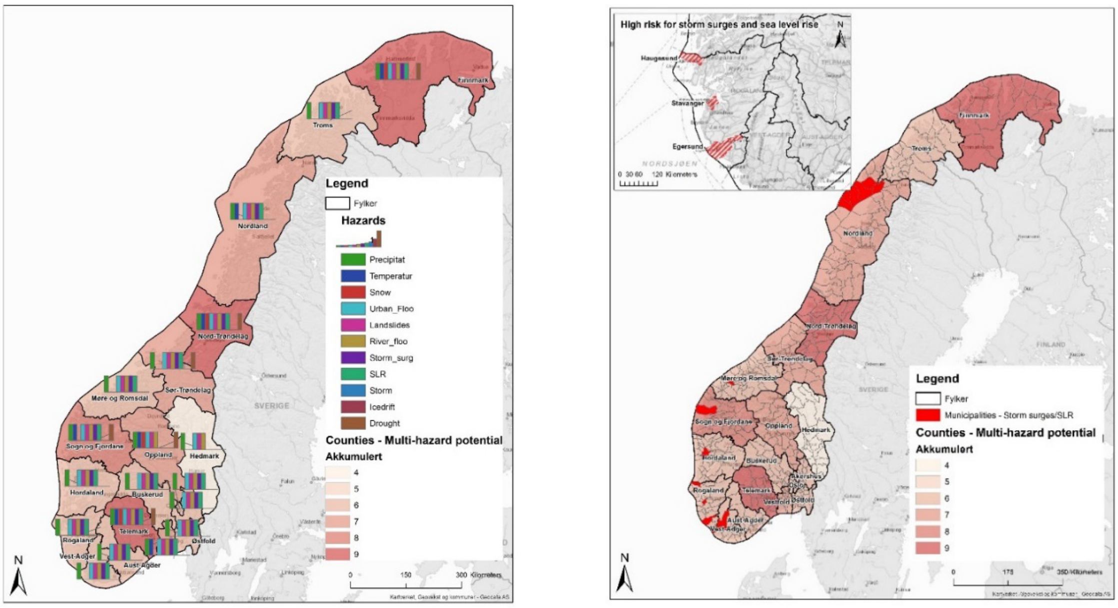


Figure 4-2: left: County overview showing hazards expected to increase in a future climate scenario; right: Municipalities with increasing coastal risks (storm surges and sea level rise, SLR), inset: municipalities with future increased coastal risk within Rogaland county.

The next step will then be to compile the meteorological base data for the site/region. This will typically be:

- Monthly precipitation normals for the reference periods 1961-1990 and 1971-2000
    - eKlima (http://eklima.met.no) for station data
    - seNorge-grid values for selected reference points (through MET)
    - Extreme value statistics from eKlima (http://eklima.met.no)
- Future precipitation scenarios

Future expected precipitation changes for the different climatic regions in Norway can be extracted from the Norwegian climate service (https://klimaservicesenter.no). These numbers, together with the precipitation normals then give the baseline for the precipitation to be expected in the future. Table 4-2 gives an example for the region "Østlandet", for the years 2045 and 2065, with the RCP scenario 8.5, also known as the "business as usual"-scenario.

Table 4-2: Expected increase in precipitation per season (in %) for "Østlandet" with the RCP8.5 scenario. Scenario "medium" = median value from several regional climate models; the scenarios "low" (10 percentile) and "high" (90 percentile) indicates the spread between low and high climate projections (https://klimaservicesenter.no).

2045	Season			
Scenario	DJF	MAM	JJA	SON
low	2.5	2.0	-5.0	-4.8
medium	16.1	16.2	3.2	4.8
high	29.0	20.0	15.5	17.5

2065	Season			
Scenario	DJF	MAM	JJA	SON
low	10.0	7.0	-7.5	-5.5
medium	16.7	21.5	2.1	7.4
high	27.0	31.0	20.0	16.5

5 Recommended approaches for selected hazards

5.1 Flooding

5.1.1 Urban flooding

Figure 5-1: Urban flooding in the Stavern crossing, 29.6.2012 (Østlandsposten, photographer: Kari Goverud).

Surface water and urban flooding is mainly caused by intense rainfall events. In areas with a large proportion of impervious surfaces, runoff will primarily take place on the surface and through the drainage-pipe network. If rainfall exceeds the capacity of the drainage network or access to this network is restricted, for example due to clogged drains, the consequence will be flooding (Figure 5-1). Hanssen-Bauer et al. (2015) specify that future surface-water challenges could be more relevant than today, due to the fact that episodes of heavy rainfall are expected to increase substantially both in intensity and frequency. In areas where much of the population is concentrated along the coast and in cities with challenges concerning urban densification, it is particularly important to consider potential surface-water hazards during urban development processes.

Terrain and impact analysis for urban flood risk management

To estimate the hazard, terrain analysis can be used to deduce how water would drain. It is recommended to use a digital terrain model (DTM) with a high spatial resolution. Where available, the use of a digital surface model (DSM) would be recommended, i.e., a model representing the earth's surface and all objects (such as buildings, dense forest, larger natural and artificial open draingage channels, etc.) on it. In contrast to a DSM, a digital terrain model (DTM) represents the bare ground surface without any objects like plants and buildings. Digital elevation model (DEM) is often used as a generic term for DTMs and DSMs (https://en.wikipedia.org/wiki/Digital_elevation_model).

In Norway, the DTMs with the highest resolution currently available are based on last-return airborne laser scanning data and are freely available from the Norwegian Mapping Authority. By 2020, such data should be available for the entire country. If a DTM is used – which often is the only type of model available – the computaion of drainage lines is a pure terrain analysis, not taking into account surface conditions, larger culverts and the like. Drainage lines can therefore be regarded as a description of how the water would drain if all culverts and the piping systems would be inaccessible. Results of such analyses can be plotted on maps, e.g., maps showing the extent (Figure 5-2) and/or the volume of natural depressions where substantial quantities of water presumably would be filling up during heavy precipitation. By combining these maps with, e.g., damage data from the insurance industry, areas where actual imapcts due to extreme weather events have occurred can be identified. Such maps also enable estimation of how long it takes for a given precipitation event to fill these depressions. Along with registered overflow and capacity calculations for sewer systems, such maps can then be used to prioritize further as part of the risk management. Experience from episodes of heavy rainfall in, for example, the city of Oslo indeed shows that water mainly seeks and follows surficial drainage lines, because the capacity of the subsurface drainage system is often reached fairly quickly during extreme weather events. Still, flood risk in other areas can not be ruled out, so such calculations can only be used as a starting point for further investigations.

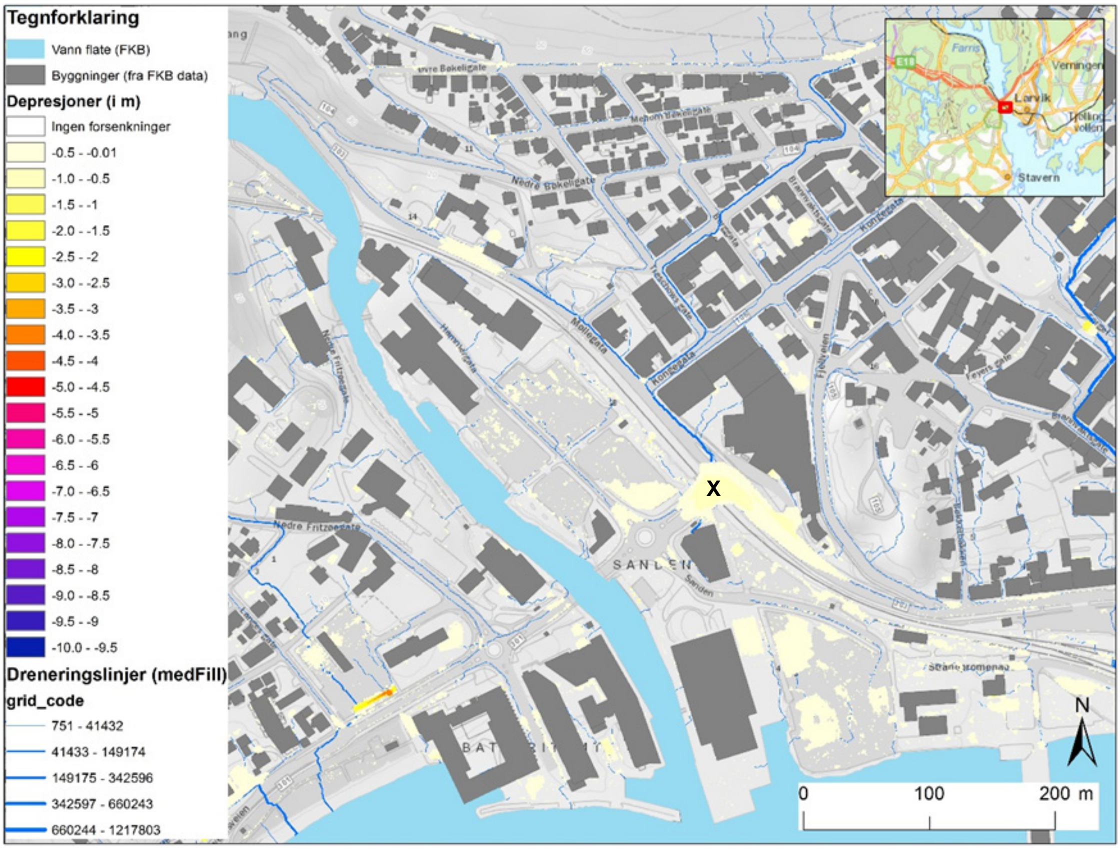


Figure 5-2: Map showing natural depressions in the city centre of Larvik. The black X marks the location of the Stavern crossing (Figure 5-1), a street crossing prone to storm water flooding during heavy precipitation events. The colour scale indicates the depth of the depressions from near zero meters (light yellow) to up to ten meters (purple; only areas outside this map perimeter).

5.1.2 River flooding

Figure 5-3: The July 2007 flood in Numedalslågen, Vestfold (Photography from NVE).

Climate changes in terms of increased annual precipitation together with an increase in frequency and intensity of heavy rainfall (cf. Hanssen-Bauer et al., 2015) will cause more frequent and more intense river flooding (Figure 5-3). Flooding may also be shifted to other seasons of the year than what has been normally observed; this is partly because the expected increase in temperature and precipitation will in most places be more pronounced during winter, and partly because snow- and icemelt will occur earlier in spring (and in many places decrease towards the year 2100). Increased flooding will also cause more pronounced erosion and more landslides. In addition, sea level rise and more intense storm surges (Subsection 5.2) will increase the effects of flooding around river outlets.

Area maps for flood risk management

For the assessment of river flood risk for the purpose of climate adaptation, the objective is not to produce something similar to the NVE flood hazard maps, but rather to present (with a minimum of input data available) areas prone to flooding under predicted climate changes. The use of such flood area maps in areal/urban planning will provide a basis to minimize future flood damage risk.

A flood hazard assessment typically consists of four main parts:

1. Compilation of background material
    a. River and terrain transects

   b. Sketches of bridges, dimensions of drainage network
   c. Historical events (for model calibration)
      i. Hydrometric gauges
      ii. Flood marks
2. Hydrological flood analysis
3. Hydraulic calculations
4. Production of flood area maps

Lack of accurate river-bed data can partly be improved by calibrating the model based on hydrometric observations from previous extreme flood events and accurate river-surface profiles at normal flow. High-resolution laser data are important for the hydraulic model improvment.

Maps are produced, e.g. for events recurring every 200-years, and for 200-years plus "climate change add-on" events. Recommended values for climate change add-on values are found in the county overviews on http://www.klimatilpasning.no/fylkesoversikt/. Through the use of GIS, the number of various kinds of exposed elements at risk can be quantified.

5.1.3 Risk reduction measures for urban and river flooding

The most important measures that can help to minimise flood risk are:

1. Considerate management of land use and localization of human-valued assets. The flood area maps will show areas exposed to flooding, and which areas that are considered safe. A safety margin should be added for each measures to drain the local water.
2. Regulation of waterways.
3. Measures to avoid blockage of the existing drainage network or to avoid considerable reduction of the drainage capacity of the network. Thereby avoiding that water builds up or finds alternative routes (that are most often undesired). Knowing the critical points of the existing drainage systems enables preparedness and subsequent actions at the right places.
4. Improvement of river capacity and drainage system
5. Elevation of areas, flood dikes, flood walls.
6. Elevation of buildings, make them flood resistant

5.1.4 Probabilistic hazard assessment for flooding in urban areas and rivers

To implement urban flooding into the framework for probabilistic hazard assessment (Subsection 6.2), we have to quantify the probability density distributions for the input parameters (mostly precipitation and drainage capacity). The first priority is to gain access to probabilistic quantitative precipitation forecasts that can be combined with urban drainage models if available. The long-term weather forecasts on yr.no (langtidsvarslene) are examples of such probabilistic forecasts, i.e., they can be directly used in the probabilistic model approach (outlined in Subsection 5.2). These weather forecasts are based on the European Centre for Medium-Range Weather Forecasts Ensemble Prediction System (ECMWF-EPS). The ECMWF-EPS represents uncertainty in the initial conditions by creating a set of 50 forecasts starting from slightly different states that are close, but not identical, to the best estimate of the initial state of the atmosphere (the control). Each forecast is then based on such an ensemble, thus representing also the influence of model uncertainties on forecast error. The divergence, or spread, of the control plus 50 forecasts gives an estimate of the uncertainty of the prediction on that particular day.

In a next step, information regarding the capacity (mean, maximum) of the drainage-pipe network needs to be obtained. Such information has to be provided by the water and sewerage authority (Vann- og avløpsetaten) of the municipality or city where the hazard assessment shall be carried out. The probabilistic rainfall forecasts are then used as (temporal and spatial) input to the sewer model to produce probabilistic forecasts of the sewer system capacity.

To implement river flooding into the framework for probabilistic hazard assessment (Subsection 6.2), we have to quantify the probability density distributions for the input parameters (water supply by upstream observations and/or precipitation as well as snow- and icemelt).

The result of the modelling is flood intensity described in terms of water discharge [m^3/s] which is applied to assess elements at risk in terms of inundation, impact loads, or erosion. The duration of a flooding event is typically 1-3 days, and the spatial extent is local to regional (e.g. a larger water course or a part of the country). The significance of the duration varies strongly on which assets are considered.

Return periods must be deduced from databases/analyses such as the commercial HYDRA II from NVE, project reports from previous flood hazard mapping, analyses from the NIFS project (NVE, 2015), etc. Annual flood discharges from river gauge stations are used to estimate extremes. However, extreme value analysis of flood water level at a gauge staion gives information of extremes only at this point. Hydraulic models are used to transform the extreme discharge to other parts of the river system. Empirical discharge equations based on topographical and hydrological catchment characteristics are used in ungauged catchments. Especially in smaller cathments, rainfall-runoff models (such as HBV) can be used to find runoff from extreme rainfall events.

Possible interrelations between the input parameters must also be determined, e.g. both water levels (inundation) and discharge depend on hydrometric observations and on the complexity of the terrain. Moreover, the local terrain may protect certain areas from water impact (loads, erosion), but not from high water levels. Interaction with storm surge should also be considered.

Typical uncertainties in flood intensity are related to rating curves (flow [m^3/s] vs. stage [m]), small number of observed extremes and limitations of the hydraulic model, and observations of present climate which may not be representative of future scenarios. Uncertainties in discharge frequencies (percentiles) can be estimated from observational data and used to calculate variations in the hydraulic model.

The Norwegian regulations for safety against flooding are based on acceptable probabilities of flooding for various safety classes of buildings. If an event may cause danger for lives, the safety class probabilities for landslides should be applied; for moderate consequences, depth-velocity products are applied (DiBK, 2011; §7.2). A typical reference return period is 20-1000 years. The most critical facilities (highest safety), should not be located in flood-prone areas (DiBK, 2011; §7.2).

5.2 Storm surge and sea level rise

Figure 5-4: Storm surge in Kabelvåg during extreme weather event "Berit", november 2011 (Lofotposten, photographer: Jan Ivar Rødli, Promo Norge).

Norway has 279 coastal communities with a potential risk for storm surges and coastal flooding. Especially the counties Rogaland and Hordaland are exposed to high storm surge water levels and have a high potential for damages in the coastal cities, e.g. Bergen or Stavanger. Northern Norway is also expecting higher storm surge water levels in the future. An investigation by DSB (2015) shows that six of ten Norwegian coastal municipalities have been affected by one or more storm floods over the last 15 years. In the last thirty years, flooding and material damages occurred in 1987, 1990, 2005 and 2011 (www.vannstand.no, DSB 2015). Lowe and Gregory (2005) as well as Debernard and Röed (2008) have investigated future changes of storm surge heights in Norway finding that these will increase in the future. Whether this will lead to severe consequences depends on different parameters, such as wind speed and direction, water level and wave heights, topography, buildings and infrastructure, etc.

Storm surge events trigger a range of hazards and impacts in coastal areas. Major storm surge-related hazards are storm, heavy rainfall, wave impact, high water levels, and inundation (Figure 5-4). Impacts or consequences from storm surge hazards may include loss of life, injuries, damages to buildings, roads, bridges, and critical infrastructure, interruption of supply chains, rising ground water levels, urban flooding/flash floods, pollution, salinization, erosion or sedimentation (see Table 5-1).

Table 5-1: Storm surge hazards and impacts

Impacts Storm surge hazards	Los of life	Injuries	Damage to buildings and inventory	Damage to roads, tunnels and bridges	Damage to critical infrastructure (electricity, fire, etc.)	Direct/indirect impacts on industry and commerce	Rising ground water levels	Flash floods	Erosion	Sedimentation	Pollution and saltwater intrusion	Impacts on coastal ecosystems
Strong winds	x	x	x		x							x
Waves	x	x	x	x	x	x			x		x	
Inundation	x	x	x	x	x	x	x		x	x	x	x
Heavy rainfall						x	x	x	x			
Sea level rise				x			x		x		x	x

Storm surges often occur in combination with other hazards such as intense rainfall, flash floods or river flooding. Coincidence of these events might lead to significantly higher water levels, e.g. in urban areas or at river mouths. Moreover, they may trigger cascading hazards and consequences: Examples might be:

- Storm surge → inundation → erosion → salinization or pollution of (drinking) water and soil → health problems in the affected population …
- Storm surge → wave impact → erosion and flooding → loss of life → destruction of buildings → destruction of critical infrastructure → fire → interruption of electricity → interruption of supply changes …

Storm surges and climate change

According to Simpson et al. (2015), climate change in the Norwegian coastal regions will lead to more frequent and intense precipitation as well as sea level rise. Sea level rise is varying along the coast, and has to be considered in combination with land uplift, which is ongoing. Due to the balance between global SLR and isostatic processes, local sea level is expected to be highest in South-Western Norway and in Northern Norway (Figure 5-5).

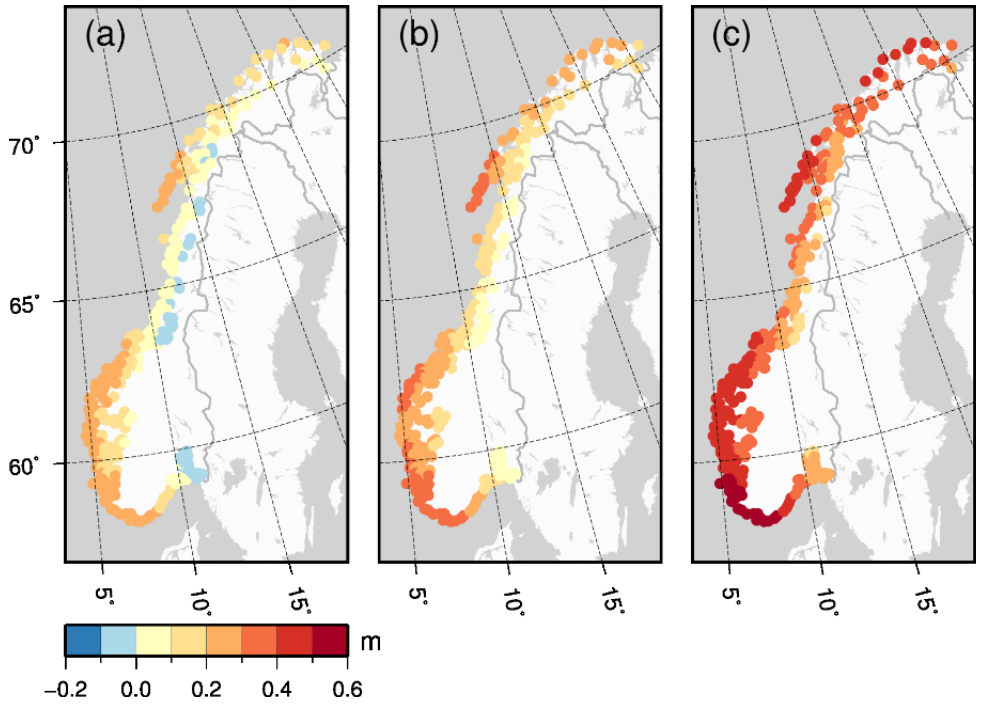


Figure 5-5: Projected ensemble mean regional relative sea level change (m) over the period 1986-2005 to 2081-2100 for the climate scenarios (a) RCP2.6 (b) RCP4.5 and (c) RCP8.5 (Simpson et al. 2015).

Sea level rise will increase storm surge water levels. Therefore, future storm surges are expected to be higher, cause more damages and reach further inland. Accompanying hazards such as increased rainfall and (although with uncertainty) increased storminess during a storm surge event would additionally increase water levels along the coast.

Approach to storm surge risk management

To analyze the risk of storm surges in the framework of an overall risk assessment, the following approach is designed (see also Figure 5-8):

1) Hazard analysis, including the probability of occurrence of storm surges and high water levels, the probability of flooding, hydrodynamic modelling of waves and inundation.
2) Vulnerability analysis, estimation of the consequences including the damages to people, property, infrastructure, and environment that might occur for various hazard intensities.
3) Risk analysis, i.e. combining 1) and 2) for the identified elements at risk
4) Risk evaluation, assessment and management, including the identification of suitable mitigation measures for risk treatment

5.2.1 Hazard analysis

A hazard analysis of coastal flooding aims mainly at quantifying the probability of storm surge water levels and related inundation on land. Numerical hydrodynamic modelling is a main tool in a hazard analysis to determine the magnitude of storm surge hazards. To model and estimate storm surge hazards, all relevant parameters have to be taken into account: wind (direction, speed, duration, fetch), offshore water levels, tides, coincidence with natural frequencies of bays, harbours, river discharge, possible interaction with flooding in river outlets, as well as relative sea level rise (corrected for isostatic effects). The local impact is determined by the output in tems of coastal water level and wave heights. The local impact also depends on the bathymetry (influencing on the waves), the topography, as well as the geometry and the dynamics of coastal features like beaches and natural barriers. Figure 5-6 summarizes the main input data and methods for a storm surge hazard analysis.

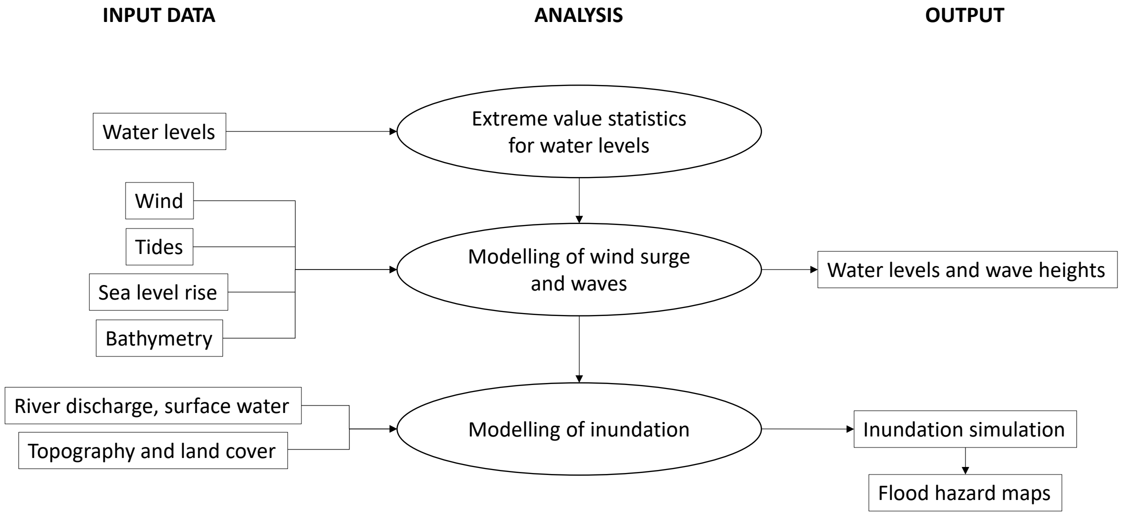


Figure 5-6: Input data and methods for a hazard analysis of storm surges.

Hazard analysis step by step:

1) Data collection: As the first part of a hazard analysis, data need to be collected and prepared for storm surge and inundation modelling Table 5-2. Data on wind, water level and tides can be derived from the local/regional gauges and measurements. Local variations of sea level rise are documented in recent reports on climate change in Norway. Bathymetry, topography and land cover data are available in dedicated databases. Surface water and river discharge can be derived from volume calculations or hydraulic modelling.

Table 5-2: Input data for storm surge hazard analysis and modelling

Input data	**Description**	**Sources, Norway**
Wind field	velocities, direction and duration -> *shear stress (N/m ^{2}, Pascal)*	http://eklima.met.no, Kjeller Vindteknikk (KVT)
Water level	at boundaries, derivation of a *storm surge curve*, including tides, eigenoscillation (seiches), external waves -> *m above MSL, refer to local reference levels*	Gauges, Se havnivå, http://www.kartverket.no/sehavniva/
Tidal data	local tidal variations, HAT	Se havnivå, http://www.kartverket.no/sehavniva/
Sea level rise	Sea level rise taking land uplift and subsidence into account	DSB (2016), Simpson et al. (2015)
Surface water, river discharge	river discharge, precipitation, others	Gauges, discharge volumes from modelling
Bathymetry	high resolution in the near shore zone to account for wave breaking -> *raster grid, flexible mesh*	Geodatasenteret AS
Coastal structures	e.g. dikes, revetments, breakwaters -> *height, slope, width of the crest, berm width and height*	Survey and mapping, Laser scan data
Topography	for inundation simulations -> *Raster grid, flexible mesh*	Geodatasenteret AS, laser scan data, Kartverket.
Land cover	-> bottom friction -> *Manning, Chezy, n as raster grid*	Land cover or high resolution land use maps

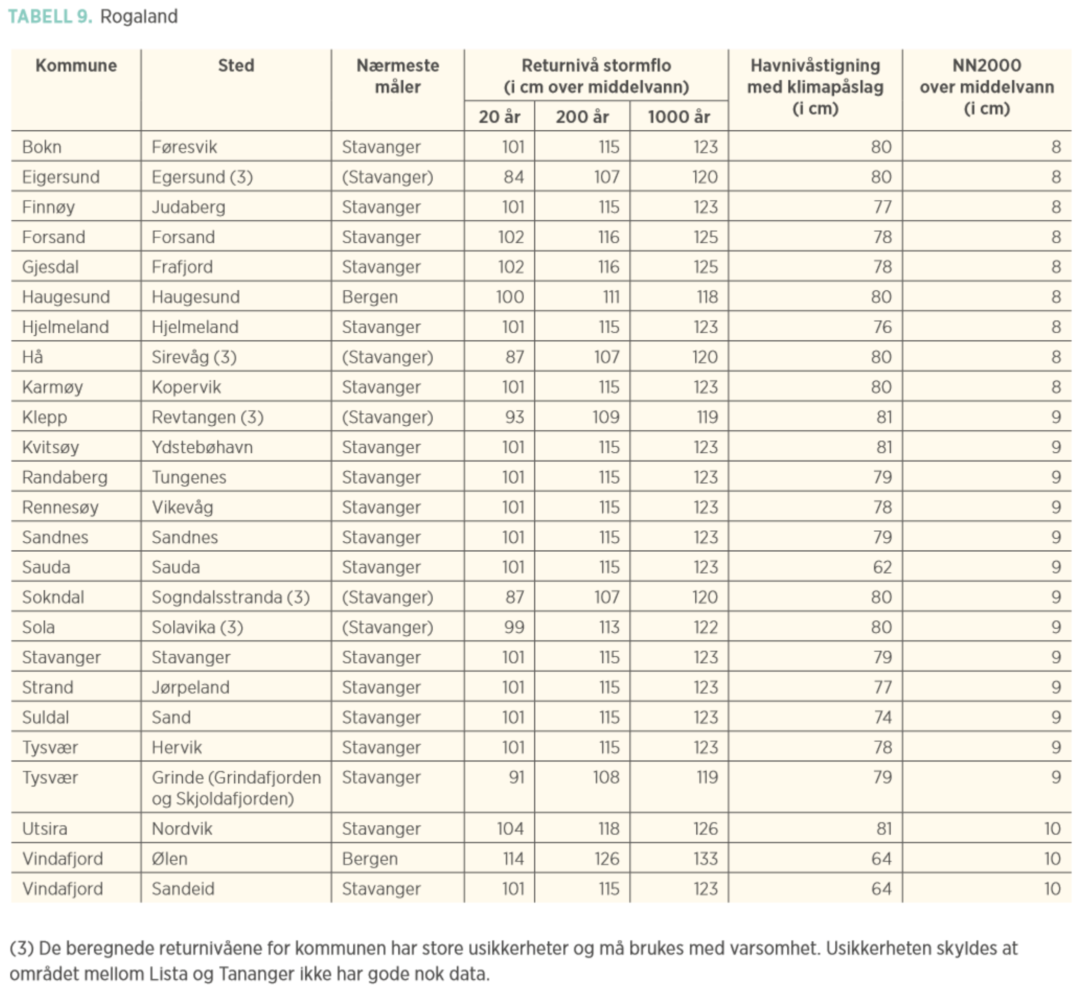
2) Extreme value statistics: water levels, tides, return periods from local tide gauges to determine scenarios for storm surges.
3) For the general methodology, it is recommended to use numbers provided for the Norwegian Municipalities by DSB (2016). According to DSB (2016) these numbers are recommended and harmonized to be used by the municipalities for their risk and vulnerability assessments, coastal planning, and climate change adaptation. For more detailed information as well as mean and maximum values, see Simpson et al. (2015). DSB (2016) provides the following data for the calculation of water levels (see Table 5-3 for an example):

    - 200 year storm surge water level for the Norwegian coastal communities. This number is based on extreme value statistics by Simpson et al. (2015). In the calculations, local/regional tide gauge data are used. The calculations include also atmospheric pressure and wind set-up on a regional scale. The local effects of wind set-up and waves have to be modelled separately. Data can be derived from eKlima (http://eklima.met.no)
    - Sea level rise for 100 years is provided by DSB (2016). In the report, relative (including land uplift) values are provided for all Norwegian coastal communities. Values are mean values, since mean values are

suggested to be used for the risk and vulnerability analyses conducted by the Norwegian municipalities. Minimum and maximum values are provided by Simpson et al (2015), and statistics of water levels for different return periods along the Norwegian coast are available (e.g. http://www.kartverket.no/en/sehavniva/Lokasjonsside/?cityid=9000007). To account for climate change and uncertainties in sea-level rise scenarios, the 95th percentile has been used here. This value represents the mean value including a climate change add-on for storm surge intensity ("klimapåslag"). If this climate change add-on is not considered, an extra value could be added to account for the uncertainties when it comes to the change of wind fields and a possible increase in the intensity and the frequency of storms.

- Tides have to be considered in the scenarios (for example HAT) provided by www.sehavniva.no.

Table 5-3: Data for calculation of water levels, example for Rogaland County (from DSB, 2016).



TABELL 9. Rogaland

Kommune	Sted	Nærmeste måler	Returnivå stormflo (i cm over middelvann)			Havnivåstigning med klimapåslag (i cm)	NN2000 over middelvann (i cm)
			20 år	200 år	1000 år		
Bokn	Føresvik	Stavanger	101	115	123	80	8
Eigersund	Egersund (3)	(Stavanger)	84	107	120	80	8
Finnøy	Judaberg	Stavanger	101	115	123	77	8
Forsand	Forsand	Stavanger	102	116	125	78	8
Gjesdal	Frafjord	Stavanger	102	116	125	78	8
Haugesund	Haugesund	Bergen	100	111	118	80	8
Hjelmeland	Hjelmeland	Stavanger	101	115	123	76	8
Hå	Sirevåg (3)	(Stavanger)	87	107	120	80	8
Karmøy	Kopervik	Stavanger	101	115	123	80	8
Klepp	Revtangen (3)	(Stavanger)	93	109	119	81	9
Kvitsøy	Ydstebøhavn	Stavanger	101	115	123	81	9
Randaberg	Tungenes	Stavanger	101	115	123	79	9
Rennesøy	Vikevåg	Stavanger	101	115	123	78	9
Sandnes	Sandnes	Stavanger	101	115	123	79	9
Sauda	Sauda	Stavanger	101	115	123	62	9
Sokndal	Sogndalsstranda (3)	(Stavanger)	87	107	120	80	9
Sola	Solavika (3)	(Stavanger)	99	113	122	80	9
Stavanger	Stavanger	Stavanger	101	115	123	79	9
Strand	Jørpeland	Stavanger	101	115	123	77	9
Suldal	Sand	Stavanger	101	115	123	74	9
Tysvær	Hervik	Stavanger	101	115	123	78	9
Tysvær	Grinde (Grindafjorden og Skjoldafjorden)	Stavanger	91	108	119	79	9
Utsira	Nordvik	Stavanger	104	118	126	81	10
Vindafjord	Ølen	Bergen	114	126	133	64	10
Vindafjord	Sandeid	Stavanger	101	115	123	64	10

(3) De beregnede returnivåene for kommunen har store usikkerheter og må brukes med varsomhet. Usikkerheten skyldes at området mellom Lista og Tananger ikke har gode nok data.

The final calculation of water level serving as model input is then as follows:

100/200 year storm surge water level + local SLR (including climate change add-on) + HAT

4) Numerical modelling needs to be conducted to simulate local effects, the spatial distribution of water levels at the coast, and inundation on land. The software package used by NGI is Delft3D-FLOW for modelling wind set-up and Delft3D-WAVE for modelling waves.

   Delft3D is a world leading 3D modelling suite to investigate hydrodynamics, sediment transport and morphology and water quality for fluvial, estuarine and coastal environments. The main part of the Delft3D package is the FLOW module which calculates non-steady flow and transport phenomena generated by tidal and meteorological forcing. The application areas may be e.g. storm surge in combination with tide, flooding at river outlets and wind, salt intrusion in estuaries, river flows, floodplains etc. The WAVE module simulates the evolution of random, short-crested wind-generated waves in coastal waters (estuaries, tidal inlets, barrier islands with tidal flats, channels etc.). Typical application areas are harbour and offshore installation design as well as coastal development and management. The WAVE module is also used for wave forecast. The WAVE module is coupled with the FLOW module. It is also possible to include effects of erosion and sedimentation through the modules SED (short term) and MOR (long term). The modules FLOW, WAVE and MOR are all available as open source (http://oss.deltares.nl/web/delft3d).

The aforementioned methodology and the Delft3D modelling approach have been applied in the project: Lardal og Larvik kommuner – tilpasning til klimaendringer (NGI, 2016a; see also https://www.ngi.no/Nyheter/Aktuelt-fra-NGI/Larvik-Lardal-foerst-med-pilotprosjekt-for-klimaendringer). In this pilot study, storm surges and sea-level rise were considered in a multi-hazard approach for Larvik and Lardal municipalities. To analyse future coastal flood risk in Larvik as a consequence of high water levels, waves, and wind, statistical analysis of sea state parameters were performed and numerical modelling with Delft3D-FLOW/WAVE was conducted to produce high-resolution inundation maps. These maps can serve as a basis for climate change adaptation planning in the municipalities. Examples from a case study in Larvik are shown in Figure 5-7.

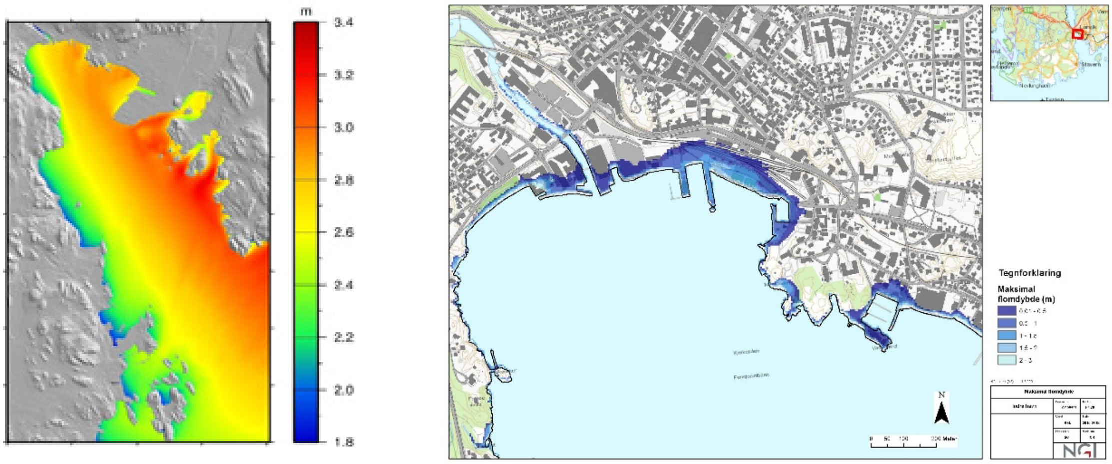


Figure 5-7: Example for numerical modelling with Delft3D in Larvik, showing maximum values for combined effects of wind surge, waves, 200-year storm surge level, sea- level rise (2065) and climate add-on (NGI, 2016a).

5.2.2 Consequence analysis

In a consequence analysis, the potential impacts from storm surge hazards are determined based on the exposure of elements at risk in the flood-prone area and their vulnerability, i.e., their susceptibility to be harmed. The severity of storm surge consequence depends on (summarized from Reese (2003), Pistrika and Jonkman (2010), Thieken et al. (2005), Penning-Rowsell et al. (1994), Kelman and Spence (2004), Merz et al. (2004, 2007):

- inundation depths
- strong winds and rainfall
- flow velocity
- duration of flooding
- wave impact
- sediment (mainly sediment transported onshore)
- water ingredients (flotsam, contamination, chemicals, etc.)
- salt concentration
- time and season of occurrence of the event
- water temperature
- flood warning and evacuation (time)
- socio-economic factors (e.g. age structure, flood experience and awareness, economic wealth or availability of insurances of the affected people)
- precautionary measures, e.g. coastal protection

Consequence analysis step by step (a detailed description of storm surge risk analysis is presented by NGI, 2013b):

1) Exposure analysis, mapping the spatial distribution of the elements at risk, including:

- the distribution of population
- buildings and inventory
- roads, bridges, infrastructure
- industrial and commercial places
- critical facilities
- land cover, land use

2) Vulnerability analysis
Determination of characteristics that make elements at risk particularly vulnerable. These can be manifold depending on local conditions.

According to literature by Reese (2003), Birkmann (2006), Jonkman (2007), and Taubenböck et al. (2008) the following vulnerability factors are here considered most relevant for coastal flood risk assessment:

- **Building type**, i.e. building material, quality and shape, or the presence of cellars. Building type is relevant when it comes to structural damage. Concrete reinforced buildings have a higher capacity to withstand hydrodynamic forces than wooden buildings and thus cause less structural damage.
- The type of **infrastructure** such as material and quality of roads or bridges is relevant for the structural damage as well as for emergency management during and after an event (escape routes, supply and accessibility) and thus contributes to vulnerability.
- The presence of **critical infrastructure** (hospitals, power stations, airports, etc.) in the affected area is important for the coping capacity. In case of a severe destruction of major lifelines (e.g. water and power supply), emergency management and recovery are hampered, leading to more severe flood impacts.
- Former flood events have shown that the age structure of the affected population is an important vulnerability factor. Elderly and disabled people as well as children have shown to be more vulnerable than others and make up a major part of the fatalities or people harmed.
- **Financial contribution to climate change adaptation**. Investments in adaptation measures or insurances (from the government, private, etc.) contribute to protecting persons from future impacts, and allow rapid recovery and rebuilding/rehabilitation of housing.
- The presence of **coastal protection measures**, **early warning systems** and a **well-informed and prepared society** reduce the amount of damage and mitigate loss of life. Persons who receive a proper warning, know where the evacuation routes are located and where to store savings (for example on the second or third floor) will be much less affected by the flooding.
- The **environmental status** is of importance for the overall vulnerability. An intact coastal environment provides a natural buffer from flooding, i.e. by coastal forests and dunes, and can therefore reduce flood impacts.

3) Damage analysis

To quantify damages so called ‘damage functions’ are widely applied. Damage functions, often called ‘depth-damage functions’ when related to flooding, describe the damage (repair or replacement costs, expressed for instance in % of value) e.g. of buildings as a function of hydrodynamic forces (most commonly indirectly expressed by water level) and the buildings' resistance (Pistrika and Jonkman 2010, Thieken et al. 2005, Reese 2003).

When using damage functions for storm surges, it must to be taken into account that different damage functions should be applied in the near shore zone, where high flow velocities and wave impact cause the major damage, and further inland, where rising water levels are the main damage factor. Hence, for coastal flooding, different damage functions have to be developed for different zones related to the distance to the coast (Jonkman et al. 2008a, 2008b; Genovese et al. 2011). Damage functions for flooding related to storm surges have been developed by Reese (2003), Pistrika and Jonkman (2010), Jonkman et al. (2008a, 2008b), and within the HAZUS software (Scawthorn et al. 2006, Friedland 2009). They have mainly been developed for different types of buildings (one storey, two storeys, > two storeys), but also for inventory, industrial buildings or infrastructure.

Despite the wide application of depth-damage functions, a weak correlation has been shown to exist between the flood depth alone and the damage (Pistrika and Jonkman 2010). Pistrika and Jonkman (2010) applied the depth-velocity product for different hazard zones instead of using the flood depth only, obtaining an improved correlation.

5.2.3 Risk assessment and mitigation

A general framework for a storm surge risk analysis is presented in Figure 5-8.

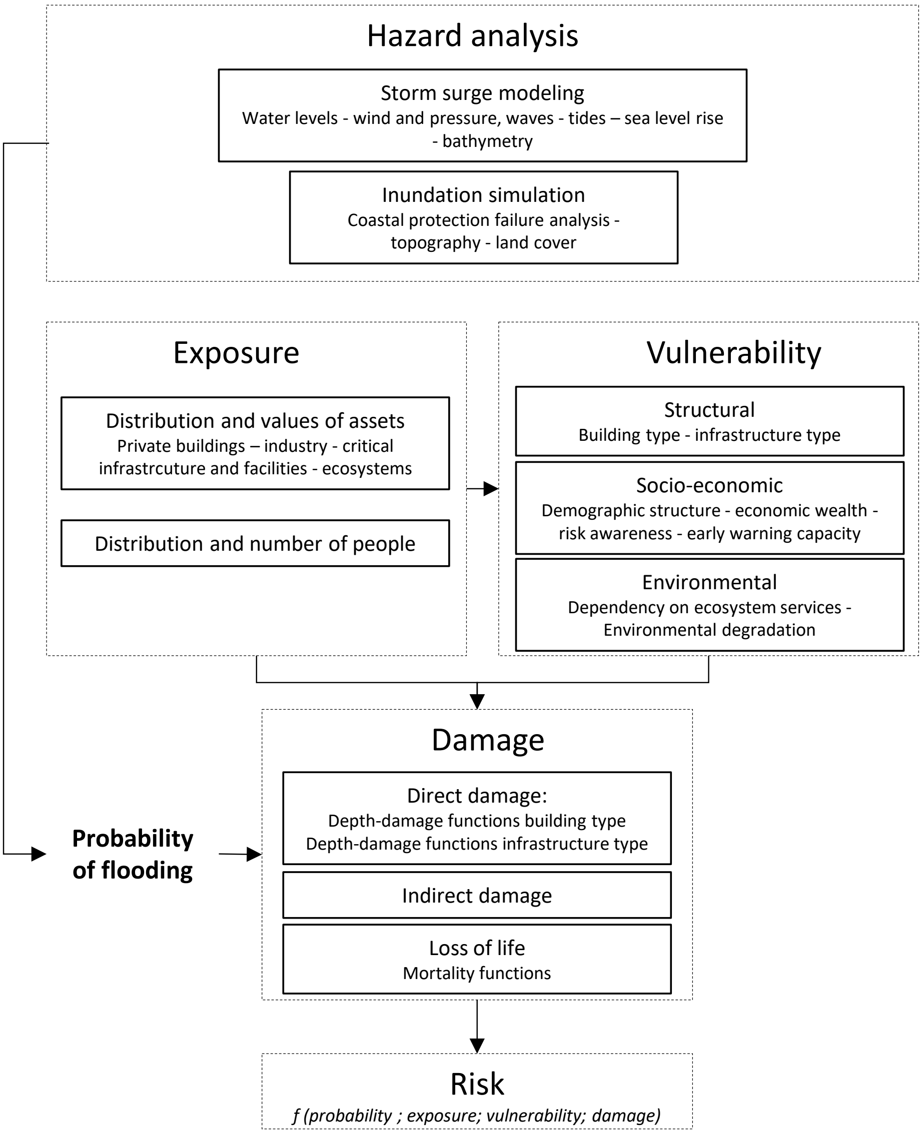


Figure 5-8: Conceptual framework for storm surge risk analysis.

Once risk has been estimated and high-risk areas have been identified in the subsequent risk evaluation phase, suitable risk mitigation measures can be selected, designed and implemented. Most common strategies to mitigate impacts from storm surges are:

Strategic planning:

- Raising budgets for climate change adaptation in coastal zones
- Risk- and vulnerability assessment, risk mapping
- Coastal planning, adaptation to higher water levels
- Protect critical infrastructure: remove or protect electricity, water, telecommunication, schools, hospitals, railway, etc. in the flood prone areas.

- Early warning systems, evacuation planning
- Building restrictions and building codes
- Public information about flood risk

Erosion protection:

- Beach nourishment
- Vegetation
- Groins, gabions, sandbags, revetments

Flood protection:

- Dikes, sea walls, revetments
- Storm surge barriers
- Breakwaters
- Land rising
- Adaptation of drainage systems and pump systems
- Private protection (e.g. flood gates, cellars)

5.2.4 Probabilistic storm surge hazard analysis

To implement storm surges into the framework for probabilistic hazard analysis (Subsection 6.2), it is necessary to quantify the probability density distributions for the input parameters (wind, storm surge level, tide level). Return periods must be deduced from the data bases presented in Table 5-2, see also e.g. http://www.kartverket.no/en/sehavniva/Lokasjonsside/?cityid=9000007

Storm surge intensity is usually described by offshore water levels, wind, tides, river discharge, and duration (as opposed to coastal water levels and wave heights, onshore flow depth above terrain or inundation height above sea level, inundation distance, etc., which are results of the modelling applied to estimate damage to elements at risk in terms of flooding, wave loads, or erosion), see Figure 5-6. The duration of a storm surge event is typically 6-24 hours, and the scale of investigation is local to regional (e.g. North Sea).

Possible correlations between input parameters must also be determined, e.g. both water levels and wave heights depend on the wind (speed and direction) and on the complexity of the terrain. However, the local terrain may protect certain areas from waves, but not from high water levels. It should further be noted that the return period of the wave height can be significantly shorter than that of the corresponding storm surge event (for sake of simplicity, these are considered to be mutually independent). Interaction with river outlet discharge and flooding should also be considered.

The Norwegian regulations for safety against flooding and storm surge are based on acceptable probabilities of flooding for various safety classes of buildings together with depth-velocity products (DiBK, 2011; §7.2). A typical reference return period is 20-200 years. For the most critical facilities (highest safety), the largest nominal annual probability of flooding or storm surge should not exceed 1/1000 (DiBK, 2011; §7.2).

5.3 Landslides

Figure 5-9: Landslide at Hedrumveien in Larvik, 24.12.2013 (Østlands-Posten, photographer: Knut Utklev).

The term landslide defines any downslope movement of a mass of soil or rocks by the effect of gravity. This mass comprises solid particles and voids, which can be filled partly or totally with water or air. An example of a landslide is shown in Figure 5-9. The physical behaviour of the downslope movement is termed landslide mechanism. The type of material in the landslide mass combined with the mechanism define by convention the basic types of landslides.

Table 5-4 lists the most common types of landslides in Norway as a combination of the type of material and mechanism.

Table 5-4. Most common types of landslides in Norway. Adapted from Cepeda (2013), using the naming convention by Cruden and Varnes (1996).

Mechanism → Material ↓	Slide	Flow	Fall
Soil			
• Earth (1)	Clay slide	Clay flow slide (3)	
• Debris (2)	Debris slide	Debris flow	
Rock	Rock slide	Rock avalanche (4)	Rock fall

Note:

(1) < 80% sand and finer
(2) > 80% sand and finer
(3) There are several types of earth flows, but the predominant ones in Norway are the quick clay landslides, or clay flow slides, using the terminology by Hungr et al. (2001).
(4) Conventionally, a landslide of the flow type involving fragmented rock is named rock avalanche (Hungr et al., 2001).

In terms of processes, three zones can be identified in the footprint of a landslide:

- Release or initiation area: the uppermost part of the footprint. For landslides initiated by rupture, the release area is the rupture area. For landslides initated by progressive erosion (i.e., no surface rupture), the release area is the zone upstream from where the sediment concentration corresponds to the transition from runoff/flood water to a sediment rich flow (e.g., > 20% by volume, see FLO-2D (2012)).
- Transition zone: the path of the landslide along which there is little or no deposition. Significant erosion may occur in this area.
- Deposition area: the zone where most of the landslide mass is deposited after the movement stops. There may be some erosion, but the deposition process dominates in this area.

In terms of risk mitigation, two of the most important factors for selecting appropriate measures are the type of landslide and the zone along the footprint where the measure will be applied.

5.3.1 Scale of investigation

The evaluation of hazard, vulnerability and risk is connected to a scale of investigation that defines both the requirements for the spatial resolution of the input data, and most importantly, the applicability of the resulting products. Table 5-5 shows four suggested mapping scales depending on the applications.

Table 5-5: Landslide mapping scales and their application (Fell et al., 2008).

Scale description	Indicative range of scales	Examples of zoning application	Typical area of zoning
Small	< 1:100 000	Landslide inventory and susceptibility to inform policy makers and the general public	> 10 000 km^2
Medium	1:100 000 to 1:25 000	Landslide inventory and susceptibility zoning for regional development; or very large scale engineering projects. Preliminary level hazard mapping for local areas.	1 000 - 10 000 km^2
Large	1:25 000 to 1:5 000	Landslide inventory, susceptibility and hazard zoning for local areas. Intermediate to andvanced level hazard zoning for regional development. Prelminary to intermediate level risk zoning for local areas and the advanced stages of planning for large engineering structures, roads and railways. Preliminary to intermediate level risk zoning for local areas and the advanced stages of planning for large engineering structures, roads and railways.	10 – 1 000 km^2
Detailed	> 1:5 000	Intermediate and advanced level hazard and risk zoning for local and site-specific areas and for the design phase of large engineering structures, roads and railways.	< 10 km^2

5.3.2 Clay flow slides (or quick clay landslides)

Conditioning factors

Higher overpressure at bedrock level due to higher rate of snow melt following extreme conditions.

Triggering factors

- Toe erosion along riverbanks or on ravines
- Increased driving forces due to higher weight of layers above ground water table following receding flooding

The most common natural causes that lead to quick clay landslides are erosion in rivers and in brooks. Climate change will produce increased hazard for erosion as a result of extreme precipitation and increase in floods in rivers and brooks in the future. In the meantime, it is difficult to establish the relation between erosion and longterm climate changes, hydrology, and quick-clay landslides. In addition, many factors are of local nature. It is worth mentioning that since the 1970s, more than half of all large quick-clay landslides in Norway are triggered by human activity.

Runout conditions

High mobility (long runout distance and high velocities) due to high water content in landslide mass. In many events initiated in subaerial conditions, the runout zone extends into water bodies (lakes or fjords) producing waves. Depending on the conditions at impact, the water waves can be of significant height when reaching shorelines (cascading hazards).

Hazard and exposure analysis

The basic information for identifying quick clay zones is:

- Presence of marine clay
- Topografic conditions
- Results of site investigations

When taking into account climate change effects, the following aspects are relevant for hazard estimation in areas prone to quick-clay landslides:

- On slopes on riverbanks and shorelines, quick reduction in water levels (e.g., after recession of flood waters)
- Potential for erosion-induced undercutting of slopes due to high velocity of runoff or river flow
- Long term precipitation or snow melting which produces changes in groundwater conditions

Since velocities and flow depths can be significant in terms of impact to exposed elements, the reference intensity parameter for hazard analysis must defined as a combination of both variables.

Exposed elements at risk both at the initation area (scarp) and on the runout zone must be identified as part of the risk analysis. Exposure conditions for potential inundation due to induced water waves should be accounted for.

Risk mitigation measures

Table 5-6 presents possible risk mitigation measures and whether they mitigate hazard, exposure, or vulnerability.

Table 5-6: Possible risk mitigatiuon measures for clay flow slides.

Mitigation measure	Mitigating
• Counterfills at the foot of slopes	Hazard
• Continuous monitoring of ground water conditions over long periods, in order to estimate response of pore water pressures under extreme events and to improve the basis for analyses and recommended measures • Improve spatial coverage and quality of site investigations for identification and evaluation of areas susceptible to quick clay landslides	Exposure
• Updating of guidelines and standards based on experience from historical cases	Vulnerability

5.3.3 Debris slides and debris flows

Conditioning factors

Steep slopes combined with coarse sediments (predominantly sand, gravel and coarser materials) are characteristic of areas prone to debris slides and debris flows. These conditions can be found on tributary rivers in the upper parts of catchments.

Triggering factors

- Toe erosion due to increased runoff in ravines or water flow in tributary rivers.
- Slope erosion and bulking of runoff until the flowing mass has the mechanical characteristics of a landslide (i.e., transformation from a flash flood into a debris flow).

Runout conditions

Mobility (runout distance and velocities) directly proportional to water content in landslide mass.

Hazard and exposure analysis
The basic information for identifying areas prone to this type of landslides are:

- Presence of loose coarse sediments
- Steep topografic conditions
- Geomorphological features

When taking into account climate change effects, the following aspects are relevant to account for in hazard evaluations of areas prone to debris slides and flows:

- Potential for erosion-induced undercutting of slopes due to high velocity of runoff or river flow.
- On slopes on riverbanks and shorelines, relatively rapid reduction in water levels (e.g., after recession of flood waters).
- Long term precipitation or snow melting which produces changes in groundwater conditions.

Since velocities and flow depths can be significant in terms of impact to exposed elements, the reference intensity parameter for hazard analysis must defined as a combination of both variables.

Exposed elements at risk are found mainly in the runout zone (but also at the initation area , i.e. the scarp) and must be identified as part of the risk analysis.

Risk mitigation measures

Table 5-7 presents possible risk mitigation measures and whether they mitigate hazard or exposure.

Table 5-7: Possible risk mitigatiuon measures for debris slides and debris flows.

Mitigation measure	Mitigating
• Improve resistance of surface to erosion by modifying land cover (new or better types of vegetation, geotextiles, etc.) • Improve surface drainage in order to reduce erosion potential	Hazard
• Continuous monitoring of ground water conditions over long periods, in order to estimate response of pore water pressures under extreme events and to improve the basis for analyses and recommended measures • Improve spatial coverage and quality of site investigations for identification and evaluation of susceptible areas	Exposure

5.3.4 Rock falls and avalanches

Conditioning factors

Steep and fractured rock slopes are susceptible to these types of landslides. Particularly important is the relation betweeen the geometry of discontinuities (joints, fractures and fissures) with respect to the slope geomorphoogy. As long as the discontinuities and the slope produce a kinematically feasible mechanism, the area should be subjected to a more detailed hazard evaluation.

Triggering factors

- Increased water pressure along discontinuities due to regional variations in ground water conditions (changes in infiltration rates of rainfall and snow-melt).
- Mechanical wedging of ice in discontinuities during freeze-thaw cycles.
- Mechanical wedging of tree roots in discontinuities.

Runout conditions

Mobility (runout distance and velocities) related to conditions of the terrain surface along the landslide path, to the volume and degree of fragmentation of rock masses during detachment and runout, and the mobilisation mechanisms (sliding, bouncing and rolling).

Hazard and exposure analysis

The basic information for identifying areas prone to this type of landslides are:

- Presence of fractured rock masses in steep terrain with unfavourable joint orientation with respect to slope surface.
- Steep topografic conditions.
- Terrain conditions on the runout zone (topography and land cover).

When taking into account climate change effects, the following aspects are relevant to account for in hazard evaluations of areas prone to rock falls and avalanches:

- Changes in freeze-thaw patterns.
- Long term precipitation or snow melting which produces changes in groundwater conditions.

Since velocities and boulder size (or avalanche depth) can be significant in terms of impact to exposed elements, the reference intensity parameter for hazard analysis must be defined as a combination of both variables.

The exposed elements are found mainly in the runout zone. Exposure conditions for potential inundation due to induced water waves should be accounted for.

Risk mitigation measures

Table 5-8 presents possible risk mitigation measures and whether they mitigate hazard or exposure.

Table 5-8: Possible risk mitigatiuon measures for rock falls and avalanches..

Mitigation measure	Mitigating
• Scaling of rock slopes (removing of loose blocks) • Removal of trees which have root systems with potential for mechanical wedging in joints in the rock slopes • Installation of bolts and anchors, and eventually wirenets and rock strips • Shotcrete can be used over bolts and anchors if the rock surface is very fractured • Installation of drainage systems if seepage is observed or expected • Drainage can also be used as a safety measure by building ditches behind the top of rock slopes in order to lead water away and thus avoid building up of water pressure in the joints	Hazard
• Larger scale measures include deflection dams, walls or fences. These measures are intended to stop or limit the mobility rock fall/avalanche in the runout zone. They do not prevent initiation • Rock fall fences are also protection measures that can be used to control the mobility in the runout zone. These fences are simple to install, but require supervision and maintenance	Hazard/exposure

5.3.5 Probabilistic landslide hazard analysis

To implement landslides into the framework for probabilistic hazard analysis (Subsection 6.2), it is necessary to quantify the probability density distributions for the input parameters (geomechanical properties, groundwater conditions, runoff and flood water levels). Landslide intensity is normally described by the combination of the depth (thickness) and velocity of the landslide mass, which are results of the modelling applied to estimate damage to elements at risk in terms of impact loads. Possible interrelations between the input parameters must also be determined, e.g. permeability, a geo-mechanical property, has a consequence on groundwater conditions.

Return periods must be deduced from data bases prepared for the relevant settings and location. The Norwegian regulations for safety against landslides are based on acceptable probabilities of landslide impact (DiBK, 2011; §7.3). A typical reference return period is 100-1000 years. For the most critical facilities (highest safety), the largest nominal annual probability of landslide impact should not exceed 1/5000 (DiBK, 2011; §7.3). However, these return periods are calibrated and used in practice mainly for snow avalanches only. For quick clay slides, a factor of safety based on the requirements in the NVE (2014) Guidelines is used rather than annual probability.

For further descriptions of probabilistic analysis for landslide runout, see Cepeda et al. (2013). It should also be mentioned that a probabilistic approach for snow avalanches is presently being developed under the NGI SP4 Project 20140053 Snow Avalanche Research, WP2 "Statistical approach for avalanche hazard zoning and warning". In this approach, the factors for triggering (probability of given weather conditions such as snow height, temperature, wind, precipitation, and slope angle, etc.) are combined with a statistical run-out model. The probability of triggering is based on qualitative "expert"-judgement using a so-called fuzzy inference system on the parameters involved. The result is the spatially referenced probability for a given location to be hit by a snow avalanche, for either forecast or hazard mapping.

6 Multi-hazard and multi-risk analysis

Many regions of the world are exposed to, and are affected by, a number of different hazards. A best-practice assessment and mitigation of the risk posed by those natural and man-made threats at a given location would require a multi-hazard and multi-risk analysis approach. This approach accounts for the possible interactions among the threats. The importance of adopting this approach lies in the fact that numerous case studies have shown that the total risk estimated when incorporating interactions between multiple hazards and risks is likely to be greater than the sum of the individual parts.

The concept of “multi-hazard analysis” may be understood as the process “to determine the probability of occurrence of different hazards either occurring at the same time or shortly following each other, because they are dependent from one another or because they are caused by the same triggering event or hazard, or merely threatening the same elements at risk without chronological coincidence” (European Commission, 2010). From this definition, it is easy to recognise that multi-hazard is a broad concept with different possible interpretations as will be shown in Subsection 6.1.

The concept of "multi-risk analysis" extends that of multi-hazard by including the other two macro-factors of risk, i.e., vulnerability and exposure of human-valued assets. Considering vulnerability, for instance, an initial event would leave a community more susceptible to future, possibly different, hazards, e.g., an earthquake weakening buildings which are damaged further by windstorms. The temporal dimension may also include changes in exposure, e.g., increased urbanisation, altering the total risk to an area, while repeated events lessen a community's resilience. Multi-risk analysis can be conducted for direct risk, i.e., direct economic losses or casualties, or for indirect risk, e.g., reduced business activity or the loss of cultural heritage.

6.1 Multi-hazard analysis: conceptual interpretations

In general terms, one can split the multi-hazard concept into two possible lines of applications, where multi-hazard analysis may be seen as: (1) the process of estimating different (independent) hazards threatening a given (common) area (Subsection 6.1.1), and (2) a means of identifying and assessing possible interactions and/or cascade effects among the different possible hazardous events (Subsection 6.1.2).

The subsequent Subsections (6.1.1, 6.1.2, and 6.2 were originally produced under the NGI GBV2016 2B3 Project 20160259 "GBV2016 2B3 Climate adaptation in risk assessment and vulnerability analysis: A probabilistic framework for risk assessment" as a contribution to SP6 GRAM. In order to illustrate the applicability of the multi-hazard framework based on Bayesian Networks, the original description also includes a case study of rockslide triggered tsunamis (see NGI, 2016b).

6.1.1 Different (independent) hazards threatening a given (common) area

This interpretation of multi-hazard analysis is the most commonly found in the literature. In fact, most of the multi-hazard risk initiatives start from the identification of different hazard sources within a given region of interest, and evaluate each individual hazard independently, generally using a hazard-specific analysis methodology. The objective is to identify the spatial distribution of the effects of the different hazards over a range of their respective intensities, and to estimate their occurrence probability or return period. The final results, according to the scale of the specific problem, are generally presented as single hazard maps, layers (in a GIS environment), aggregated maps (overlapping all the maps), and hazard curves (for each hazard) that plot the probability (or return period) against the intensity measure of the hazard (e.g., Grünthal et al., 2006; Carpignano et al., 2009; Schmidt et al., 2011; Harbitz et al., 2016).

The main effort within this multi-hazard perspective, as found in the literature, is the harmonisation of the hazard analysis for the different threats. This is generally considered a fundamental requirement in multi-risk analysis to make the risks posed by different threats comparable (e.g., Marzocchi et al., 2012, Garcia-Aristizabal et al., 2015). What differs the various multi-hazard approaches within this context in the literature is carried out.

6.1.2 Hazard interactions, triggering or cascade effects

A multi-hazard analysis considering interaction/triggering effects is, in general, a more demanding process compared with the independent consideration of different hazards. In this type of analysis, the occurrence of one hazardous event could change the probability of occurrence of another event (leading to potential cascades). The typology of interactions that can be grouped under this name are in fact phenomena in which the physical process of interest is a pure triggering mechanism in which an initial event produces a perturbation that, when acting on a given system, may bring it to an unstable state, forcing it to find a new equilibrium. Reaching this new equilibrium may imply the occurrence of an event that, in this case, may be said to be triggered by the initial one (Gasparini and Garcia-Aristizabal, 2014). The link between the intensity of the triggering event (e.g., the ground shaking caused by an earthquake) and the intensity of the triggered event (e.g., a volume of mass moving down a slope) is governed by complex physical mechanisms that are intrinsically related to the specific triggering and triggered events. This fact, and the ubiquitous random effects that may affect these processes, make probabilistic approaches the most promising way for the quantitative characterization of such interactions (e.g., Gasparini and Garcia-Aristizabal, 2014; Garcia-Aristizabal et al., 2015). In this way, chains of events can be considered in the risk analysis. For example, a landslide, which itself might have been triggered by an earthquake or heavy precipitation, may lead to other events such as, for example, the formation of a landslide dam, which could then lead to the dam breaching, debris flows, river sedimentation, etc. (Zhang et al., 2013). Another well-known example is the 2011 Tohoku earthquake triggering a tsunami, which again caused the catastrophe at the Fukushima nuclear power plant (Synolakis mad Kânoğlu, 2015).

Although most of the multi-risk literature mentions this as an important item to be considered in hazard and risk analyses, the available studies that explicitly consider cascade effects and interactions remain rare (e.g., Marzocchi et al., 2012; Mignan et al., 2014; Gill and Malamud, 2014). A possible explanation could be that the necessary input data, and sometimes the complexity of the hazard ‘chains’ that can be foreseen, often discourage the analyst to consider such interactions and triggering effects in a holistic multi-risk analysis. This view is in agreement with the feedback obtained from civil protection agencies about multi-risk analysis (Komendantova et al., 2014).

6.2 Proposed framework for multi-hazard analysis

6.2.1 Basic principles

In the framework proposed, the interactions among hazards, as introduced in Subsection 6.1.2, are analyzed quantitatively with as high accuracy as the available data allows. Basically, the procedure for multi-hazard analysis can be illustrated as follows:

- Definition of the space-time window for the hazard analysis, including a set of reference return periods, for which it may be of interest to estimate hazard;
- Identification and description of the hazards (e.g. landslide, earthquake, meteorological events) impending on the selected area and potential triggering factors (meteorological, climatological, geographic, topographic, etc.);
- Identification of the selected hazard scenarios covering all possible intensities (e.g. frequency-intensity relationship) and relevant hazard interactions;
- Probabilistic analysis of each scenario.

Of particular interest in multi-hazard analysis is the description of the interactions among hazards. Considering for example two different threatening events, whose occurrence is E_1 and E_2, then the probability of E_1 occurrence (H_1) can be written as:

$$H_1 = p(E_1) = p(E_1|E_2)p(E_2) + p(E_1|\overline{E_2})p(\overline{E_2}) \tag{6.1}$$

where p represents a probability or a distribution of probability, $p(E_1|E_2)$ is the probability of E_1 occurring given E_2 occurs, and $\overline{E_2}$ means that the event E_2 does not occur, leading to $p(E_1|\overline{E_2})$ being the probability of E_1 occurring given E_2 does not occur. The generalization of this expression to more than two events does not pose any particular conceptual problem, even though it may require a more cumbersome formulation.

This general expression may represent different particular cases that can be of interest. Of particular interest are, for example, interactions that may play a role in short-term probabilistic hazard/risk analysis (e.g., of the order of days). For example, the occurrence of heavy rain (E_2) changes significantly the landslide occurrence (E_1) probability within a time horizon of days. Weather forecasts may track the time evolution of $p(E_2)$ that leads to a time evolution of $p(E_1)$ through Equation (6.1). In this case, the most challenging scientific problem is the reliable estimation of $p(E_1|E_2)$, which may be obtained by theoretical models, empirical laws, or expert opinion. It is worth remarking upon the differences this scheme has with long-term analyses; in the long-term perspective, a local landslide database already accounts for the fact that most of the landslides are due to heavy rain or storms. In other words, it is expected that the database will provide a reliable estimation of $p(E_1)$ directly.

6.2.2 Bayesian networks for multi-hazard analysis

A new quantitative multi-hazard analysis model based on Bayesian networks is introduced to estimate the probability of a triggering/cascade effect. The flexible structure and the unique modelling techniques offered by Bayesian networks make it possible to analyze cascade effects through a probabilistic framework. Furthermore, the interactions between hazards and the uncertainties involved may be captured using a Bayesian network. In particular, this methodology is well suited for treating uncertainties associated with hidden geodynamic variables, which are not directly observable from the Earth's surface (e.g., model uncertainty in causal relationships between unobservable volcanic processes and surface manifestations or monitoring data). The probabilities of hazardous events are updated on the basis of any new information gathered.

A Bayesian network (BN), also called belief network, is an emerging method for reasoning under conditions of uncertainty and for modelling uncertain domains. The method has been increasingly used in a wide variety of problems, ranging from dam safety analysis (Smith, 2006; Peng et al., 2012; Morales-Nápoles et al., 2014; Wang and Zhang, 2016), earthquake risk management (Bayraktarli et al., 2005; Bensi et al., 2011), landslide risk management (Stassopoulou et al., 1998; Straub, 2005), tsunami hazard analysis (Medina-Cetina and Nadim, 2008; Blaser et al., 2012) and multi-risk analysis (Liu et al., 2015).

A BN is a probabilistic model based on directed acyclic graph and may be expressed as

$$B_S = G(Z, E) \tag{6.2}$$

where B_s is the network's structure, Z is the set of random variables $\left(z_1, z_2 ... z_n\right)$, and $E \in Z \times Z$ is the set of directed edges, representing the probabilistically conditional dependency relationship between random variables. Each variable Z_i in the network is defined in a discrete and finite outcome space (discrete random variable) or as a continuous outcome space (continuous random variable). For discrete random variables, the probability measure $\pi\left(z\right) = P_r\left(Z = z\right) = p\left(z\right)$ is the joint probability mass function (PMF). For continuous random variables, $\pi\left(z\right) = \partial^N P_r\left(Z \le z\right) \big/ \partial_z = f(z)$ is the joint probability density function (PDF). One important property of the BN is that the joint probability function of all random variables in the network can be factorized into conditional and unconditional probabilities in the network (Jensen and Nielsen, 2007).

6.3 Proposed framework for multi-risk analysis

As stated previously, multi-risk extends the concept of multi-hazard analysis by incorporating the temporal variability of vulnerability and exposure. Multi-risk analysis allows a more complete and realistic risk estimation , and provides useful indications and criteria for decision-making in the risk management process. The approach proposed by Liu et al. (2015) is recommended here. Such approach comprises a three-level framework as illustrated in Figure 6-1.

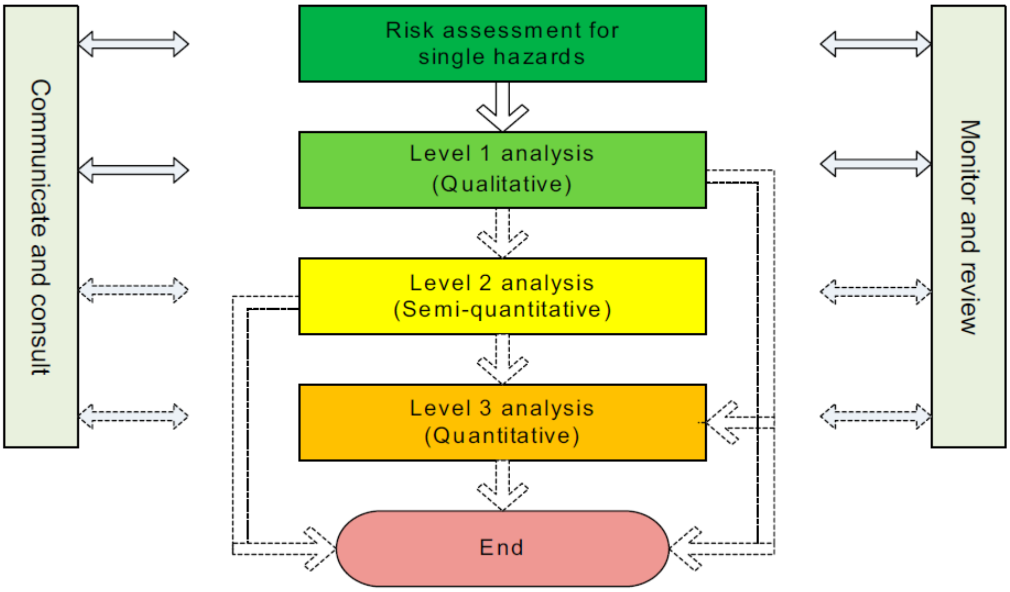


Figure 6-1: Schematic view of the steps followed in the proposed multi-risk estimation framework (Liu et al. 2015).

The Level 1 analysis is comprised of a flow chart type list of questions that guides the end user as to whether or not a multi-risk estimation approach, which explicitly accounts for cascading hazards and dynamic vulnerability within the context of conjoint or successive hazards, is required or not. The steps involved in the Level 1 analysis are detailed in Figure 6-2.

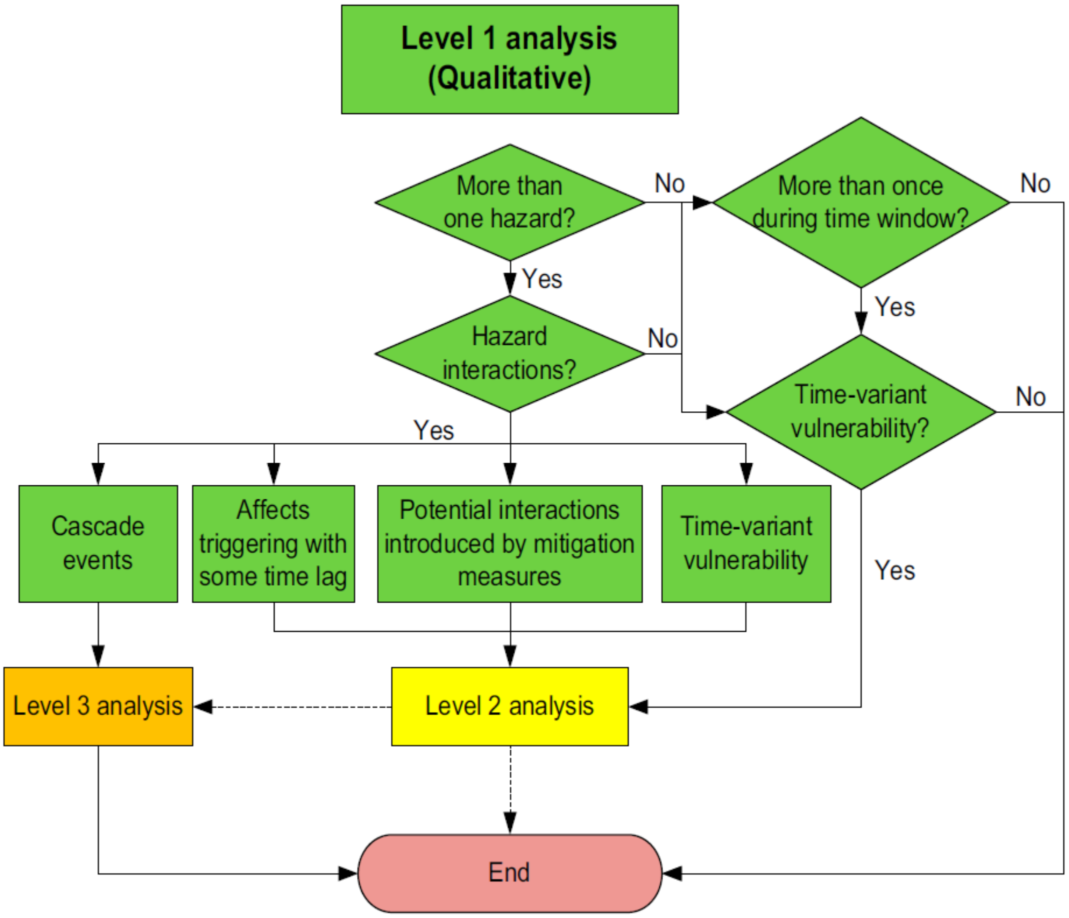


Figure 6-2: Steps involved in the Level 1 multi-risk analysis (Liu et al. 2015).

The second level is a semi-quantitative approach to explore if a more detailed, quantitative analysis is needed. The flowchart of this level of investigation is given in Figure 6-3.

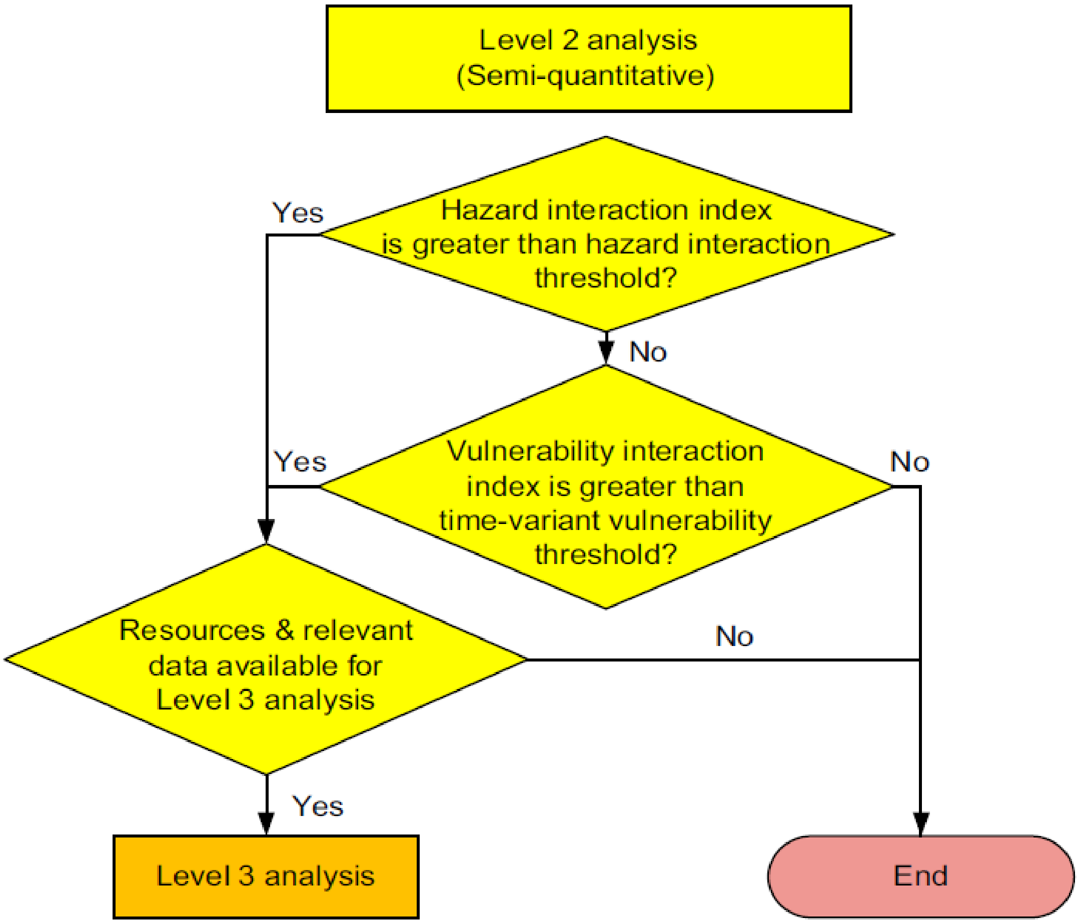


Figure 6-3: Steps involved in the Level 2 multi-risk analysis (Liu et al. 2015).

In the Level 2 analysis, the interactions among hazards and dynamic vulnerability are analyzed approximately using semi-quantitative methods. To consider hazard interactions and time-variant vulnerability at this level, a matrix approach based on system theory is applied. Semi-quantitative matrix coding method is applied to describe the degree of interaction. Quantitative criteria are provided to assess the relevance of the hazard interaction. A detail of an example implementation of this phase of the Level 2 analysis is shown in Figure 6-4.

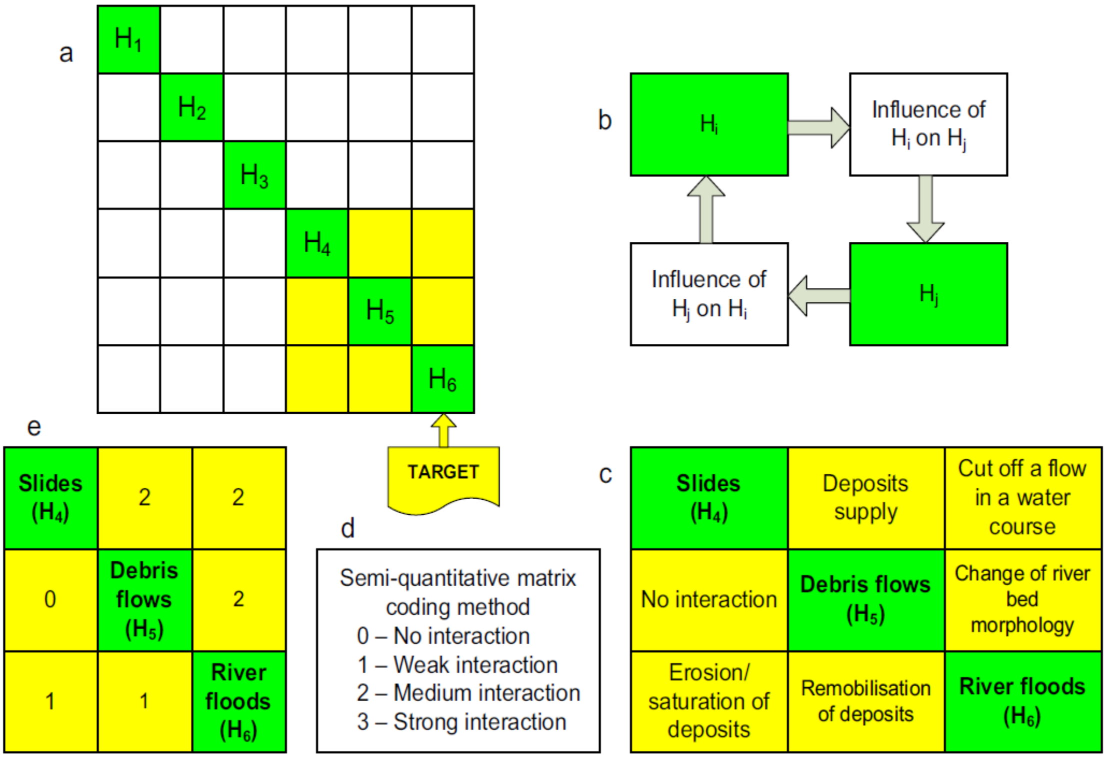


Figure 6-4: Detail of the example implementation of the matrix coding included in the Level 2 multi-risk analysis (Liu et al. 2015).

The third level is a detailed quantitative multi-risk analysis based on Bayesian networks. The Level 3 analysis allows the quantitative estimation of the effects of the interaction between different threats by estimating both the probability of triggering/cascade effects and by modelling the time-variant vulnerability of a system exposed to multiple threats. An example Bayesian network for the Level 3 analysis is shown in Figure 6-5.

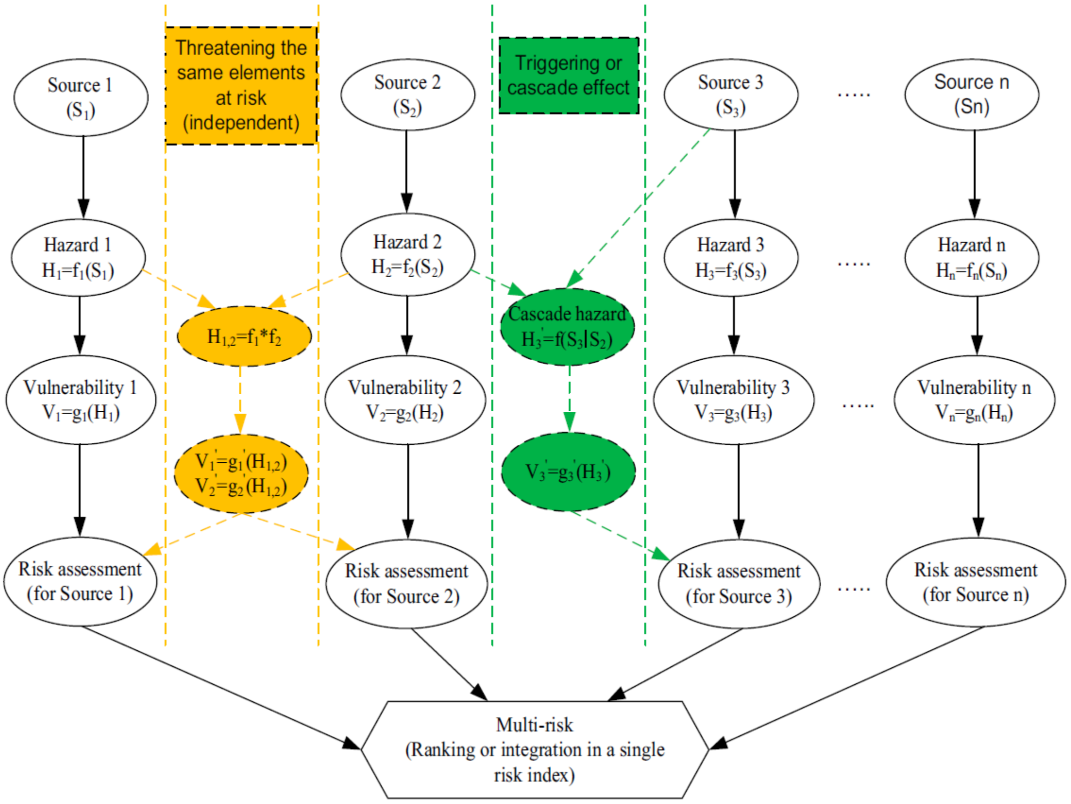


Figure 6-5: Example Bayesian network for the Level 3 multi-risk analysis (Liu et al. 2015).

For Norwegian municipalities, the main emphasis will first be put on the qualitative and semi-quantitative analysis in the risk framework.

6.4 Preliminary risk identification

The multi-risk framework presented in the previous subsection assumes that risk estimation has been performed for single threats taking into account some harmonisation requirements as given by Liu et al. (2015). Given that resources and data may be limited, it may not be immediate to identify which of the threats are prioritary in terms of hazard and of the possible impact on the area and human-valued assets of interest. In order to identify preliminarily which single-threat risk estimation efforts should be pursued prior to the multi-risk estimation process, it is useful to adopt a rational scheme for the prioritization and identification of the most relevant threats and risks.

The analytic hierarchy process (AHP) is a comprehensive and rational structured technique, based on mathematics and subjective assessment, for structuring a complex decision problem, for representing and quantifying its elements, for relating those elements to overall goals, and for evaluating alternative options based on a set of criteria. It was developed by Thomas L. Saaty in the 1970s and has been extensively studied and refined since then (see e.g Saaty 2010). The AHP is operationally structured into the following macro-phases:

1. Decomposition of the decision problem into a hierarchy of more easily comprehended sub-problems, each of which can be analyzed independently. The elements of the hierarchy can relate to any aspect of the decision problem—tangible or intangible, carefully measured or roughly estimated, well or poorly understood—anything at all that applies to the decision at hand.
2. Systematic evaluation of the hierarchical structure by pairwise comparison of its constitutive elements. In performing comparisons and quantifying two elements' relative meaning and importance, decision makers can refer to objective data or to subjective judgments. Operationally, this entails the computation of the vector of criteria weights.
3. Conversion of the evaluations to quantitative values which can be processed and compared over the entire range of the problem. A numerical weight or priority is derived for each element of the hierarchy, allowing comparison of diverse and heterogeneous elements in a rational and consistent manner. Operationally, this is reflected in the computation of the matrix of option scores.
4. Calculation of the output quantitative priorities for each of the decision alternatives. Such outputs parameterize the alternatives' relative ability to achieve the decision goal, thereby defining a repeatable quantitative ranking for objective decision making. In this phase, a quantitative ranking value for each alternative option is obtained.

The AHP can be used effectively to rank threats which are concurrent in a given (common) area. It can be seen as a tool for the prioritization of single-threats risk estimation studies for subsequent multi-risk investigations using the three-level framework proposed by Liu et al. (2015).

In applying the AHP for this purpose, the alternative options are given by the various possible threats (e.g., floods, tsunamis, landslides, etc.). The criteria to be used for ranking threats are both related to hazard (e.g., expressed as the qualitative assessment of the likelihood of occurrence of unwarranted events of a given magnitude based on historical data, physical models or other sources) and consequence on human-valued assets. Consequence includes both vulnerability and exposure of vulnerable assets. A possible set of consequence criteria could thus refer to the impact of the threat on the following dimensions of the system: (1) physical (e.g., persons, structures, infrastructures); (2) institutional; (3) economic; (4) environmental/ecological; (5) cultural; and (6) societal. Implementation of the AHP entails the compilation of the quantative matrix of pairwise comparison of the relevance of the different criteria (e.g., how relevant is the institutional impact with respect to the environmental/ecological impact?), the quantitative assignment of scores to each threat with respect to each criterion (e.g., how relevant is the impact of a landslide on the environmental dimension? On the physical dimension? Etc.) and the merging of this information through the AHP algorithm. Threats would be ranked quantitatively in a way that reflects the user inputs of both comparative relevance of criteria and scoring of attributes for each option. NGI is in the process of applying the AHP for the purpose of landslide risk mitigation decision-making (Uzielli et al., 2017).

It is not necessary to base the assignments of relevance and scores on quantitative data. The preliminary assignment can rely on qualitative information, judgment, case-specific constraints, etc. The AHP is thus to be seen as a semi-quantitative tool which allows stakeholders and decision-makers to optimize the use of available resources by identifying those threats which deserve most attention in terms of requiring risk analysis. In a best-practice scenario, once risks from different threats have been ranked semi-quantitatively using the AHP, the respective risk estimates can be pursued in view of the subsequent multi-risk approach.

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