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Hazard and risk assessment for early phase road planning in Norway

Anders Solheim[1] · **Kjetil Sverdrup-Thygeson**[1] · **Bjørn Kalsnes**[1]

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Abstract
Road construction in rugged terrain and variable, partly harsh climate is challenging. Proper assessment of natural hazards at an early planning stage can give large cost savings and safer roads. In assessing natural hazards along 720 km of planned roads in Norway, a GIS-based tool was developed to utilize publicly available data and dynamic runout models. The output is an outline of the most critical locations and serves to limit the extent of necessary field work. The Norwegian national susceptibility maps are generally conservative and using only these in the planning would give unrealistically high hazard levels. Various optimizing techniques were therefore implemented in the GIS tool and the outputs further calibrated against existing detailed hazard maps in selected locations and further validated during field work at the defined 'hotspots'. The field work comprised assessing return periods of unwanted events, probable road closure time, and relevant mitigation measures, all within sets of pre-defined ranges of values. The following consequence evaluation quantified the indirect economic consequences of closed road and assessed the consequence for emergency preparedness qualitatively. Other consequences were not considered in the study. Climate change was considered and evaluated to affect the probability for flooding and debris flows, whereas the link between climate change and the other assessed hazards was considered too uncertain to impact on the risk estimates. Results of the study were communicated through an interactive map solution, with key results presented as fact sheets activated in the map for each risk section of the roads.

Keywords Natural hazards · Risk · Roads · Norway · Climate

1 Introduction

The rugged Norwegian terrain poses challenges to road planning and construction, including threats from several different natural hazards. By performing risk and vulnerability analyses at the earliest planning phase, before the final routing is done, large savings can be achieved through early-stage planning of mitigation measures or re-routing to avoid the most challenging segments if possible.

✉ Anders Solheim
anders.solheim@ngi.no

[1] Norwegian Geotechnical Institute, Oslo, Norway

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Norway, as many other countries, has abundant publicly available data on natural hazards at a regional level, in addition to a high-resolution (1 m) digital terrain model (DEM) covering the entire country. Utilizing all available data in an optimal way has the potential of limiting the need for extensive field work, and to make field campaigns more pin-pointed and efficient.

Several previous studies focus on the consequences of natural hazards to roads, both for the vehicle itself (Voumard et al. 2013) and for costs related to road closure, as a function of the road's importance (Tacnet et al. 2012). Other studies focus on sustainable and cost-effective mitigation measures at already defined hazardous spots (Zumbrunnen et al. 2017). Chamorro et al. (2020) propose a methodology to allow road agencies and municipalities to design sustainable mitigation and recovery strategies by incorporating dimensions such as social vulnerability, probability of failure of road links and their impacts on road accessibility and mobility, using an example of volcanic hazards in Colombia. Doll et al. (2013) discuss the costs of adapting railroads and roads to weather extremes, using examples from Germany and Austria. Mejia-Navarro and Garcia (1996) made a decision support system for the road sector, which took local geology and precipitation patterns, as well as vulnerability aspects into account to predict hazards in an area in the US. Such elements are partly embedded in national Norwegian susceptibility and hazard maps, which form a base for the assessment methods presented in this paper. Several studies also focus on recovery after natural hazards events. Zamanifar and Seyedhoseyni (2017) propose a model for prioritizing the recovery operations after an event, whereas others, such as Muriel-Villegas et al. (2016), focus on the reliability and vulnerability of transportation systems, within and between urban areas.

Few studies seem to assess how existing inventories, data and maps can be combined in a smart way and used in the planning of new roads, thereby planning the necessary mitigation measures at an early stage, as well as avoiding the most hazardous locations through alternative routing.

The study presented in this paper is carried out for a state-owned Norwegian road company, Nye Veier AS, to assess potential natural hazards and their consequences along ca. 720 km of planned roads (Fig. 1) at the early planning stage, before the final route is fixed. In addition to an analysis of the hazard and risk along the planned routes, the project also developed a new hazard assessment tool, which is based on publicly available data, is easy to update as new data become available, and runs on a GIS platform. The output from the tool forms the base for planning field inspections of identified 'hotspot' locations and further assessment of the consequences and costs in case of unwanted events.

Hazards analysed and discussed here comprise snow avalanches, rockfall and rockslides, debris slides and debris flows, landslides in sensitive clay (quick clay), flooding and strong winds with snow drift. These are the most common natural hazards in Norway, threatening both buildings and infrastructure in large parts of the country. Hence, the methods developed in this project are highly relevant as first assessment tools for any natural hazard assessment project in Norway, not only along linear infrastructures, such as roads, but also for municipal land use planning, etc.

This paper focuses on the GIS based tool for early assessment of hazards, and the methods of optimizing the available data, as well as how the results were communicated to the client, an important part of the project. Field validations and the analyses of consequences, for a full risk assessment, are briefly described, but not discussed in detail.

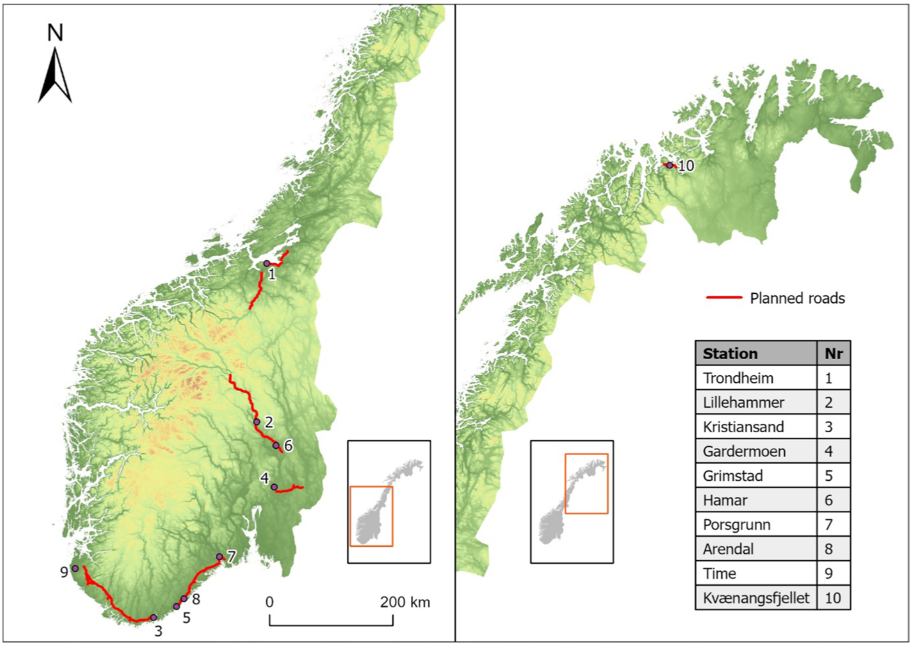

Fig. 1 Map of Norway showing the roads (red lines) assessed in the present study. Numbers on the map and the table show weather stations used in the analyses of climate and prognosed climate change

2 Methods

2.1 Data sources and optimization of data

Susceptibility maps covering the entire country for snow avalanches, rockfall, debris slides- and flows, and flooding, are publicly available from the Norwegian Water Resources and Energy Directorate (NVE), on https://kartkatalog.nve.no/#kart. These maps constitute the main background for the initial GIS-based assessment of these hazards. The susceptibility maps are based on a relatively coarse DEM (10 m resolution) and numerical run-out analyses, without field inspection, and are conservative in nature (Fig. 2). They are commonly used by Norwegian municipalities to identify areas where more detailed investigations of hazard and risk are required, and they do not include probability in the form of return periods. To produce more realistic hazard assessments along the planned road routes, various steps were taken to optimize the outputs from the GIS tool. Details on the optimization are described below for each of the hazard types.

During the GIS analysis performed in the present project, three hazard levels were classified, 1 (low), 2 (medium) and 3 (high) (Table 1). This is to be considered a rough semi-quantitative assessment of the hazard, without embedded return periods for the hazard levels. The output of the analyses provides the necessary background for further assessments and analyses, including field inspections of the identified hazardous sections of the routes and assessment of return periods.

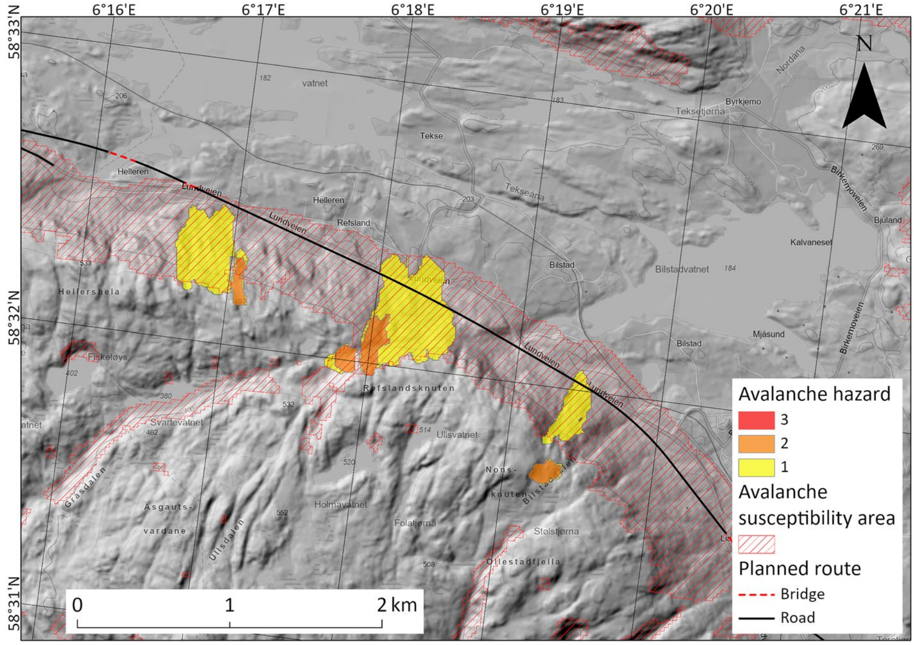

Fig. 2 Example of a GIS analysis for snow avalanches along a part of planned road E39 (black line) in SW Norway. The red pattern is snow avalanche hazard from the national susceptibility maps (www.skrednett.no). The yellow and orange fields show the avalanche hazard classes after analysing with the new hazard assessment tool

2.1.1 Snow avalanches

The publicly available national snow avalanche susceptibility maps (www.skrednett.no) are based on a DEM covering the entire country with a resolution of 25 m × 25 m. Release areas are defined from the terrain slope angle. Run-out is estimated using the empirical alpha–beta model (Lied and Bakkehøi 1980; Bakkehøi et al. 1983), which estimates the run-out from each cell in the release area (Derron and Sletten 2016). The maps, showing potential release- and runout areas are adapted for use in a map scale of 1:50.000, and the level of detail is limited by the grid cell size of 25 m. Climatic differences and vegetation are not considered, and small-scale topographic features are not detected because of the relatively coarse resolution.

The Norwegian Geotechnical Institute (NGI) has developed an improved model, NAKSIN, which runs on a DEM with 10 m resolution, takes local climate and vegetation conditions into account and simulates run-out using the program MoT-Voellmy to estimate avalanche probabilities above a set threshold probability (Issler et al. 2020). To speed up the processing time in this project, NAKSIN was run with fewer simulations (up to 100.000) than would have been the case for more detailed investigations tuned to the regulations set by the Norwegian Planning and Building Act, and a return period of 1/1000 (1.000.000 simulations). The reliability of these simplifications was controlled by running the analyses for selected areas in which field-based mapping had been performed, and then compared. The results were acceptable but led to some adjustments (below). The three

Table 1 Indicators to define the hazard classes (3: high, 2: medium, 1: low) in the GIS tool. Explanations of the indicators are given in the text sections for each of the hazard types (below)

Hazard class	Indicators					
	Snow avalanches	Rockfall	Debris flows	Quick clay	Flooding	Wind w/snow drift (days above critical limit)
3	Model threshold return period 10 years	Reach probability (RP) > 70% or RP 40–70% and mapped landslide deposit or Slope angle > 44°	Susceptibility zone and relevant recorded event in or within 50 m from zone	Quick clay hazard zone with hazard class 2 or 3	Within hazard zone or susceptibility zone and max. water level rise 5–8 m	> 10 per year
2	Model threshold return period 30 years	RP 40–70% or RP 20–40% and mapped landslide deposit	Susceptibility zone and susc. 3 or 4*	Quick clay hazard zone with hazard class 1 or Marine / fluvial deposits and slope > 1:5	Susceptibility zone and max. water level rise 2.5–5 m	6–10 per year
1	Model threshold return period 100 years	RP 20–40%	Susceptibility zone and susc. 1 or 2*	Below marine limit and marine/fluvial deposits and slope < 1:5	Susceptibility zone and max. water level rise 2–2.5 m	2–6 per year

*Susceptibility zones are based on Devoli et al. (2019) and briefly explained in the section on debris slides and debris flows, below.

semi-quantitative hazard classes for the present study are defined as described in Table 1 and an example shown in Fig. 2.

2.1.2 Rockfall

The publicly available susceptibility maps show both release and run-out areas for rockfall. These maps are also based on a DEM with 25 × 25 m spatial resolution and made for a map scale of 1:50.000. This means that small scale topography with rock ledges of up to 50 m height may not be detected as potential release areas.

To optimize the rockfall assessment, the modelling tool RockyFor3D (RF3D) (https://www.ecorisq.org/ecorisq-tools) was run along the given corridors. This is a deterministic, stochastic model, which estimates the run-out of individual blocks (Dorren 2016). To simplify and speed up the process the model was run with 'Rapid Automatic Simulation (RAS)', on a DEM with 10 m resolution. The user must set certain values, and for the present study these were rock density set to 2700 kg/m3, block dimension 1 × 1 × 1m, and a rectangular block shape. The rock density is set as an average. The geology along the investigated roads vary, but large parts go through Precambrian gneisses and granitic gneiss (southern roads) and metamorphic sedimentary rocks (mid and northern sections). Then RF3D estimates a set of other parameters, such as release areas, type of ground and rugosity, automatically from the DEM. One of the outputs from RF3D is Reach Probability (RP, in %), and the three hazard levels were determined according to Table 1. After field validation (assessment of block localization and terrain) at several locations, a cut-off RP was set to 20%, as the longest runouts from the program were considered unrealistic.

2.1.3 Debris slides and debris flows

The national susceptibility maps for debris slides and debris flows show affected areas for all types of soil landslides in steep terrain, except quick clay slides and minor detachments. The maps are based on a digital elevation model with 10 m resolution, and the level of detail is for a map scale of 1:50 000. The maps are constructed by the Geological Survey of Norway, NGU (2014), and are based on slope angle, planar curvature, size of water supplying catchment, the shallow geological conditions (taken from the maps of Quaternary deposits), and identifiable historic landslide activity. The landslide runout is estimated using a 'multiple flow direction' model in the 'FlowR' tool, which uses a probabilistic method to estimate the direction of flow (https://www.terranum.ch/en/products/flow-r/). The model does not account for vegetation, buildings or other human interventions or other features with a relief lower than that of the DEM resolution. Further details on the construction of the susceptibility maps are reported by NGU (2014).

In the assessment performed in the present GIS analysis (Table 1), we used a combination of the susceptibility zones for debris flows, classified susceptibility zones per catchment, from 1 (low) to 4 (high), and data on historic events in or near the identified hazardous zone (Fig. 3). The historic events are taken from the national landslide inventory (https://temakart.nve.no/tema/SkredHendelser). The landslide susceptibility zones (1–4) are based on work done by Bell et al. (2014) and Devoli et al. (2019), in which they used the national landslide inventory in combination with the map of Quaternary deposits, land cover, average yearly rainfall, various water runoff variables, and derivatives such as slope and aspect from a 15 × 15 m DEM, modelled at catchment level (Devoli et al. 2019).

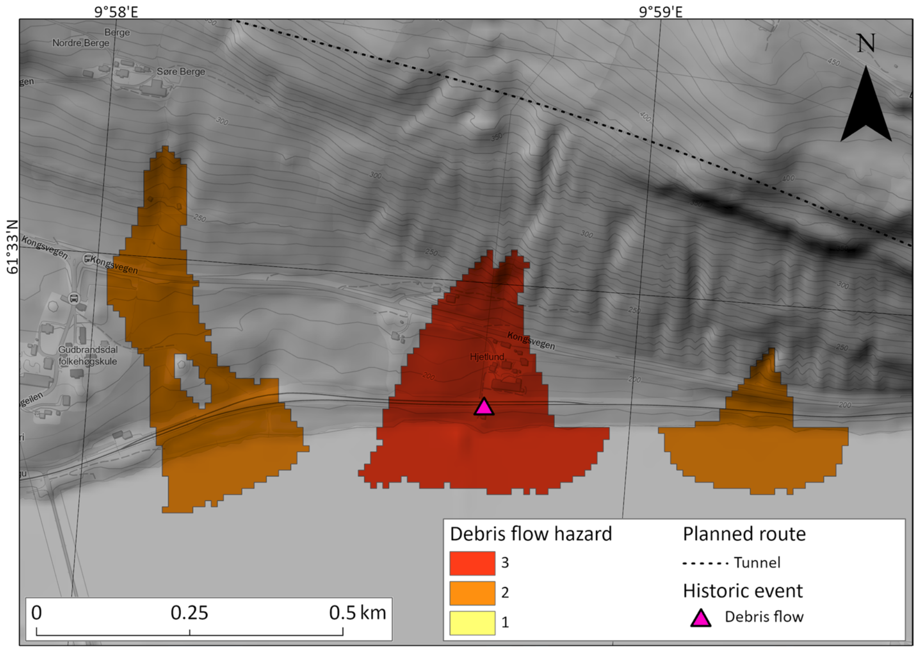

Fig. 3 Example of hazard classification of debris flows, in hazard class high: 3 (red) and medium: 2 (orange). The classification of the middle area as 3, high, is due to the recorded historic event (triangle)

2.1.4 Quick clay landslides

Very sensitive clay, or quick clay, with a brittle behaviour, is a common problem in many low-lying parts of Norway. Quick clay is developed in marine clays, deposited shortly after the retreat of the last glaciation in Norway, when the relative sea level was higher than at present. Hence, the quick clay can only be developed in areas below the Holocene marine limit, which in Norway varies from zero in the southwest, to about 220 m elevation north of Oslo. Large areas in the central southeast and in the middle parts of Norway have stability problems related to occurrence of quick clay, and the problems are also widespread along the coasts of Norway. Many parts of the country have been mapped, based on topographic criteria (https://temakart.nve.no/tema/kvikkleire) and the presence of quick clay has been confirmed by geotechnical borings, but the maps do not cover the entire country. Where they exist, the defined hazard zones are classified as low, intermediate or high hazard, 1, 2 or 3, respectively.

The present assessment (Table 1) is based on the existing hazard maps (https://temakart.nve.no/tema/kvikkleire), Quaternary maps issued by the Geological Survey of Norway (http://geo.ngu.no/kart/losmasse/), DEM with 10 m resolution, and the elevation of the marine limit, also published in NGU's maps of Quaternary deposits. The main areas of quick clay hazard are mapped as marine deposits in the Quaternary geological maps. Fluvial deposits are included in the assessment because these are often shown to stratigraphically overlay marine clays near river mouths.

2.1.5 Flooding

The available data which have been used comprise:

- Susceptibility maps for flooding (Map scale 1:50.000, without estimated return period)
- Hazard zones (return period 200 years, mainly produced for large rivers)
- Maximum flood water elevation (estimated using 25 m raster)

The susceptibility maps, produced by NVE, are based on DEMs (resolution 10 m), the areal extent of the catchments, and information from > 300 hydrological stations spread over Norway. No detailed hydraulic calculations are performed, and the areal extent of the catchment is the only variable used for producing the susceptibility maps. For catchments in the range 1–500 km^2, the following empirical equation is used (NVE, 2011):

$$dH(m) = 0,965 \cdot \ln(Area) + 2$$

where d(H) is the maximum water level rise, and 'Area' is the catchment area in km^2.

For practical reasons, the maximum water level rise is set to 2 m and 8 m for catchments smaller than 1 km^2 and larger than 500 km^2, as these values correspond to the values of the equation solved for 1 and 500 km^2, respectively. In general, this overestimates the maximum water level rise, but is considered practical for general risk assessments (NVE, 2011). For more detailed assessments of water level rise, the lake percentage and the runoff are also used (NVE 2011).

As for the other hazards assessed in the GIS tool, the flood hazard is divided in three classes (Table 1), based on maximum flood water rise, but again without introducing probability (return period) at this level in the study.

2.1.6 Wind and snow drift

Strong wind combined with snow drift is a challenge particularly at some high mountain roads, but strong side-wind can also cause problems at exposed locations, such as bridges and tunnel entrances. The analysis of wind used in the present study is based on simulations using the numeric Weather Research and Forecasting model (WRF) (Michalakes et al. 2001). One year of simulations for Norway in 1 × 1 km grid is combined with a 40-year (1979–2018) model simulation in a 4 × 4 km grid, using the long-term correction method 'quantile-regression' of Liléo et al. (2013). This gives hourly values in a 1 × 1 km grid. Based on model outputs and wind profiles at different times, the wind speed at 10 m height is estimated, and this is interpolated to a 500 × 500 m grid.

We have used the following data to estimate hazard classes (Table 1):

- Snow drift: Number of days with wind > 12 m/s, and snow fall during the last 3 days
- Wind: Number of days with wind > 15 m/s, and no snow fall during the last 3 days

The 12 m/s limit for snow drift is set relatively high, as the method does not differentiate between dry and wet snow, nor does it take rain following snow into account. The two values are then summed for each 500 × 500 m grid cell to set the hazard classes according to Table 1.

2.2 The GIS analysis

The analysis is performed within a given polygon, defined by the user. In the present project the polygon is a corridor following the planned roads (Fig. 4). In addition, one may define a buffer zone to catch potential release areas located outside of the defined road polygon, but which still may threaten the road. The size and shape of the polygon, as well as the need for a buffer zone, are defined by the user, based on the topography and the expected hazards in the area.

Because the existing susceptibility maps are unrealistically conservative and therefore often define too large susceptibility areas, the optimization described in the previous sections are performed in a GIS based tool. The tool has a simple interface, where the user selects the analysis polygon, indicates the buffer distance, and chooses one or more hazards to be included. The analysis is primarily executed in Python, but for snow avalanche and rockfall, external programs are started automatically from within Python. Processing time depends on several factors: the size of the given polygon, the number of hazard types chosen, and the number of release areas found for snow avalanche and rockfall. The tool is implemented as a script tool in ArcGIS Pro 2.4. Because the external simulations of snow avalanches and rockfall are done in a somewhat simplified way, with fewer simulations than in more detailed assessments, the run time of the analysis is quite fast. The run time depends on the number of release areas inside an analysis area, but as typical examples it may range from 30 to 5 min for NAKSIN (snow avalanche) and 10 min to 1 min for Rockyfor3D (rock fall), for areas of 82 km^2 and 48 km^2, respectively.

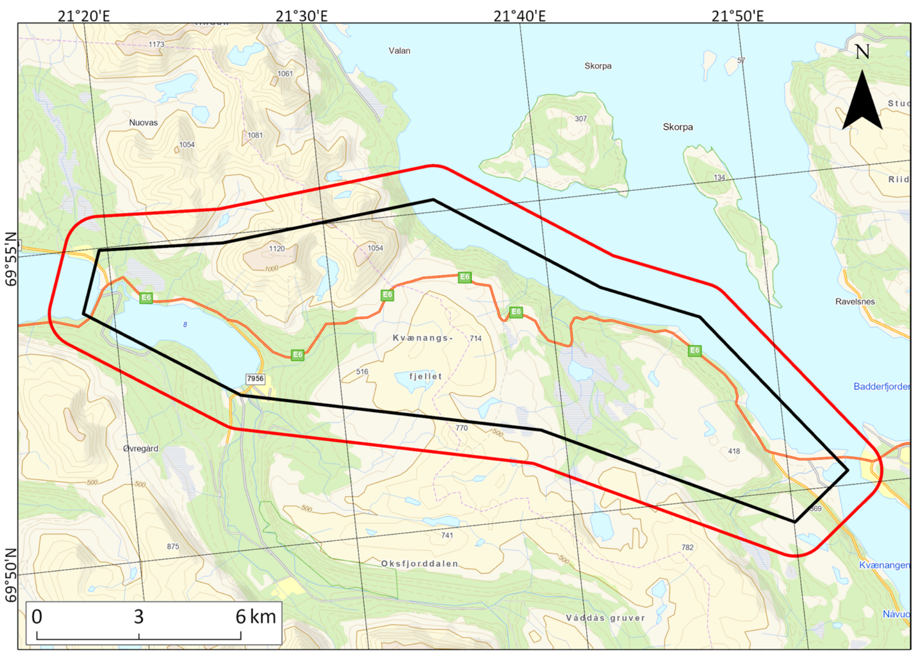

Fig. 4 Example of polygon around one of the planned routes, with a 1 km wide buffer zone (red line) around it

2.3 Validation of the GIS tool output

The validation of the results from the GIS analyses was done by (a) comparing with areas where hazard maps had been made previously, and (b) field inspection of areas identified as hazardous in the GIS analyses.

2.3.1 Comparison with hazard maps for landslides and avalanches

Norway is fully covered by susceptibility maps for snow avalanches, rock fall, debris flows and flooding. The maps form the background for identifying areas where more detailed hazard maps are needed if the area is to be developed or to assess potential mitigation needs for existing buildings or infrastructure. Landslide hazard mapping has been done at a scale of 1:10.000 for several municipalities in Norway, where the prioritizing of individual areas to map is based on risk estimates. These mapping projects involve extensive field work, in addition to analyses of terrain, vegetation, local geology and historical events. Generally, the hazard maps come out less conservative (more restricted 'red zones') than the susceptibility maps. The hazard maps for landslides and avalanches define the boundaries for events with return periods of 100, 1000, and 5000 years, affecting a 'normal' property width of 30 m, reflecting the acceptance criteria set by the Norwegian Planning and Building Act (Direktoratet for Byggkvalitet 2017). For flooding, the equivalent return periods are 20, 200 and 1000 years.

The results of the GIS analyses in the present project should be considered as a significantly improved version of the susceptibility maps and should resemble the hazard maps with a return period of 1000 years (200 years for flooding). The difference being that the return period is estimated per 1 km of road rather than 30 m. To test the results of the GIS analysis against hazard maps, two areas where hazard mapping had been performed were selected, in different parts of the country, with different types of hazards, and in different climate zones. The outcome of this gave acceptable, although still somewhat conservative results compared to the hazard maps. The hazard zones from the GIS analyses were largely consistent with the mapped zones, but often with 10–20% larger extent. The comparison resulted in the RP cut-off for rock fall at 20%, described above. Other than that, the hazard maps resulting from the GIS analyses were considered fully adequate as a base for field inspections of selected locations.

2.3.2 Field work

Field inspections were carried out for the most hazardous parts of all the roads in the project. The hazards identified in the GIS analysis were assessed and plotted individually. Hence a hazardous section could be exposed to more than one hazard. Focus was placed on identified locations with hazard level 2 and 3 (Table 1), but also several locations with hazard level 1 were inspected. In addition, some locations where no hazards were identified by the GIS analysis were visited, to verify the negative result. Several teams carried out the field inspections, and in total, roughly 150 km were inspected, either from car or by foot, depending on the complexity of the hazard(s) and whether the section was along existing road or not. The field inspections verified that the output from the GIS analysis was realistic, although often a bit on the conservative side. Hence, the field inspections served to reduce the extent of the hazardous areas further.

This was based on criteria such as the distribution of rockfall blocks, local topography, signs of avalanche activity, etc. Some identified hazard locations were classified as zero-hazard after field inspections. This had various reasons, such as inaccuracies in the Quaternary geology maps. Another reason was that close inspection of the local topography revealed natural barriers for debris flows, with the result that the problematic area could be greatly limited or eliminated.

The field work comprised qualitative assessment of the likely probability for the events identified from the GIS analyses, following a pre-defined set of return periods. In addition, the potential closure time in the case of an event, the most relevant mitigation measures, and a rough estimate of the mitigation costs were all parts of the field assessments. The probabilities are re-calculated from the thresholds of the Norwegian Planning and Building Act, based on real estate property width of 30 m, to road sections of 1 km length. The other parameters are based on experience. All these parameters were assessed using standardized forms with pre-set value classes (Table 2). This made the assessment quick and effective, but also relatively coarse. However, these assessments were only meant to be first indications to serve in a first cost–benefit analysis of the road project. The analyses carried out in this early planning stage are meant to point out where mitigation measures or re-routing should be considered, and where more detailed investigations are necessary to provide base data for detailed design of the road and the mitigation measures. The field inspections in some cases also resulted in re-routing of the planned road, with large potential economic savings as a result.

Table 2 Pre-set values ('pluck lists') used in the field inspections of hazardous sites identified from the GIS analyses

Hazard	Nominal probability	Closure time	Mitigation measure	Mitigation cost (NOK)
Flooding	1: > 0,25/year	1–2 days	Bolts, nets	Low: < 100.000
Debris flow	2: 0,25/year-0,05/year	3–4 days	Rock fall fence	Medium: 100.000–1 mill
Debris slide	3: 0,05/year-0,01/year	5 days-3 weeks	Channeling	High: > 1 mill
Quick clay slide	4: 0,01/year-0,002/year	3 weeks-3 months	Debris flow net	
Rock fall	5: < 0,002/year	> 3 months	Snow fences	
Snow avalanche			Erosion control	
Slush flow			Levelling/counterfill	
Wind/snow drift			Trench/embankment	
			Barrier	
			Stream inlet control	
			Culvert/landslide bridge	
			Bridge	
			Pipe	
			Other measures	

2.4 Consequence assessment

As for the hazard analysis, the consequence analysis also had to be simplified and efficient. It was therefore concentrated to two measures, (a) the quantified indirect economic consequence (IEC) of a closed road, and (b) the qualitatively assessed consequence for emergency preparedness. Both were based on the estimated closure time in case of an event. Estimates of closure time was based on experience from relevant cases. A large quick clay landslide may close a road for several months due to the need of extensive repair and mitigation works, whereas a small rockfall may not damage the road, which thus can be cleared in a few hours. Often, however, there is a need for inspection of release areas, which will extend the closure time. In locations susceptible to more than one hazard, which is often the case, the hazard resulting in the longest closure time was considered, as this meant the most severe consequence. IEC was analysed for each of the hazard points and based on the estimated closure time. The analyses included a map analysis of detour possibilities, the type, length, capacity and quality of the alternative road, and the traffic density of the road, estimated as average daily traffic through one year. Any effect of queues along the alternative road was also included, and the distribution between goods transport and private cars was included where information existed.

Direct economic consequences, such as costs for repair or rebuilding of the road after an event, has not been included, as these costs will need to be assessed for each individual event and would introduce more uncertainty to the estimates. Similarly, consequences for human life and health are not assessed. The probability for direct hits on vehicles, leading to injuries or loss of life is low. Estimating probability for loss of lives is complicated and would need detailed information, which this early planning phase estimates do not comprise (driving speed, width of landslide, intensity of event, type of vehicle, etc.).

The assessment of consequence for emergency preparedness includes the location of critical infrastructure like hospitals, fire stations, airports, military facilities, etc., and the estimated closure time and detour possibilities. Whether the road is of local, regional, or national importance, as well as the population density in the region, are also considered (Fig. 5).

2.5 Climate change effects

As the expected service time for roads in Norway is between 40 and 60 years (Simonsen 2010), climate change throughout this century have been assessed with regards to potential change in risk. The analysed road sections are located in different parts of the country. Norway has large regional variations in climate (Hanssen-Bauer et al. 2017), and we have therefore based the climate assessments on data from selected weather stations, relevant for the location and the climatic conditions of the specific road. However, as the current study is intended as a relatively coarse early-phase assessment, several simplifications are done.

Precipitation and wind have been considered the most important weather elements for the analysed hazards. The Norwegian Meteorological Institute has calculated Intensity–Duration–Frequency (IDF) curves for precipitation based on data from the weather stations, both for the present and for projections until year 2100. We have used data from the IDF curves to estimate the effects of climate change on debris slides- and flows and flooding. For debris slides and debris flows, most often along small streams or ravines with small catchments and short response time, we have used the prognosis for the intensity of

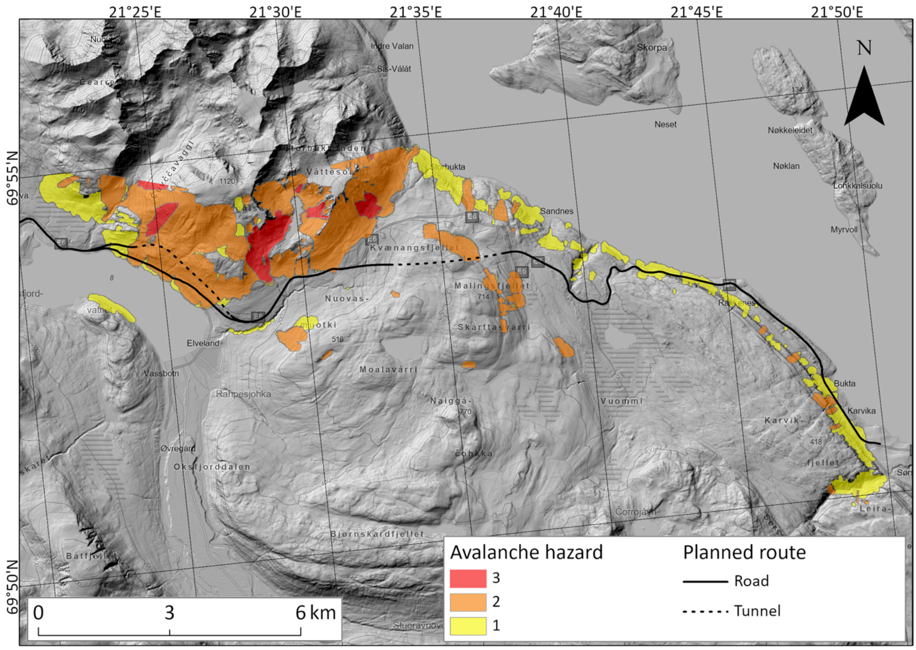

Fig. 5 Assessment of snow avalanche hazard along a planned route along road E6 in northern Norway. This is the same section as Fig. 4

precipitation with 90 min duration. For flooding in rivers in small to moderate catchments with longer response time, we have used 24 h precipitation, whereas for larger rivers, we have added a climate factor of 20% to the runoff. For the main, largest rivers, which are dominated by snow melt floods, no climate factor is added. This is in accordance with recommendations from the Norwegian Water and Energy Resources Directorate (NVE 2016).

Using Fig. 6, the return period in year 2100 for a given precipitation event is given where the 'future' stippled curve crosses the same precipitation level (Fig. 6). This approach is simplified, but it provides an indication of the expected development.

Only climate related effects on the probability, i.e., the return period of the potential hazards, have been assessed. The reasoning behind this simplification is that there are numerous factors in addition to climate, such as demographic development, type of vehicles, traffic density, etc., which will affect the consequences and lead to unacceptable uncertainty.

River floods and debris slides- and flows have the most direct link to precipitation, and the prognosed increase in precipitation towards year 2100 (Hanssen-Bauer et al. 2017) affects the estimated probability for these events at several locations. For debris flows, there are certainly a number of other factors which determine their release and severity, such as the availability of sediments. However, most debris flow- and slide events in Norway are triggered by precipitation, mostly as rain but sometimes also in combination with snowmelt (Krøgli et al., 2018; Schilirio et al., 2021; Bondevik & Sorteberg, 2021), and the availability of sediments is taken into account by including the maps of Quaternary deposits in the original assessments (described above). Most slopes where these landslides occur in Norway are valley sides with usually less than 5 m cover of glacial till above bedrock.

Other hazards, however, may also be affected by precipitation, but with a more uncertain link. Rockfall can be triggered by intense precipitation, but other causes, including

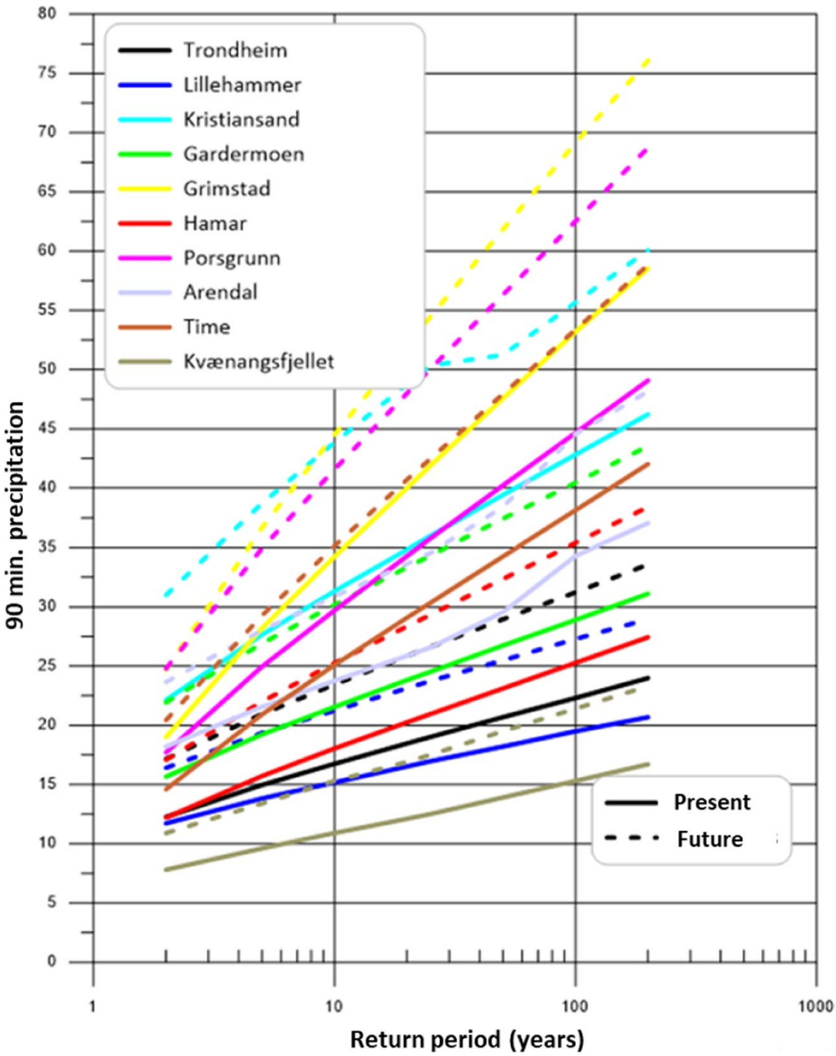

Fig. 6 Return periods for 90 min precipitation for the present situation (solid line) and for year 2100 (dashed line), based on IDF curves from selected stations used for assessment of debris flows. The curves for 'present' are taken from the IFD curved from the stations listed in the upper left corner, whereas the stippled 'future' curves represent the projected 90 min return period in year 2100. As an example of use, the 90-min rain at station Hamar corresponding to a 100-year event today is 25 mm. This is estimated to represent a 10-year event in 2100

freeze–thaw cycles, wind, roots, etc. are also important. In a study from Canada, Macciotta et al. (2017) found a slight positive correlation between dryer and wetter months and frequency off rockfall. Despite several studies, knowledge about the correlation between rockfall occurrences and factors such as temperature and precipitation, is still limited, and studies find that many rockfall events occur when other triggering factors, such as precipitation and freezing conditions are absent (Delonca et al., 2014). A comprehensive literature study was also done in a recent study by Emhjellen (2021). Due to the many triggering factors and the large uncertainty, we have therefore chosen to keep rockfall probability as of today in the assessments.

Flooding with increased erosion in riverbanks is the most common natural trigger of quick clay slides, and hence increased precipitation may have an effect. However, there are several other factors, such as local ground conditions, depth to the sensitive clay, changes in land use, as well as other human factors, etc., which affects the hazard and hence make a climate related assessment uncertain for quick clay hazard.

Although the records of historic wind data are fewer and shorter than for precipitation, there are tendencies towards increased wind fields over Norway. Stronger winds may lead to increased wind related problems at locations such as bridges and tunnel portals. Increased wind may also lead to an increase in problems related to snow drift. On the other hand, the warming trend will lead to decreased areas with snow on the ground in winters, and to shorter periods with snow accessible for snow drift. Higher elevation of the treeline also adds to this development. This all leads to large uncertainty regarding wind related problems, and we have therefore kept the return period at the present level for wind related events through this century.

Snow avalanches form a problem only at very few locations in the present study. However, increased precipitation may lead to larger avalanche hazard on the short term. However, seen through to the end of this century, reduction in both the areal extent of snow cover and the duration of the snow season, combined with a climbing treeline, will, eventually lead to a reduction in the frequency of snow avalanches. However, the probability of wet snow avalanches and slush flows may increase through the period (Jaedicke et al. 2008; NGI 2013). Due to the few relevant locations in this study, and the described uncertainties, the snow avalanche probability is kept as of today in the assessments.

In summary, due to the uncertainties discussed above, climate change effects in this study are only taken to affect the probability of flooding and debris flows- and slides.

3 Results

The combination of the initial assessment using the GIS tool, and field work in the identified 'hot spots' resulted in well documented hazard sections along the planned roads. These were coded according to return period (Fig. 7). The results were presented in an interactive map solution, again using ArcGIS Pro. Upon zooming up the map, one gets more information (Fig. 7), and by clicking one of the hazard lines, a fact sheet with more information appears (Fig. 8).

The GIS analyses identified a total of 795 segments with potential risk. However, these represent individual types of hazards, and several of the segments are overlapping, as more than one hazard may be present many places, causing different levels of risk. All hazards described in this paper constitute challenges for the planning and construction of the roads. We have indicated relevant mitigation measures, but many of the sites will have to be revisited and re-evaluated in higher degree of detail for the detailed design phase.

The combination of probability, in this case represented by one of five pre-set return periods, and consequence defines the risk, which is split in low, medium, and high, as shown in the lower right of Fig. 8. In the same diagram (Fig. 8) we have also indicated the potential shift in risk towards the end of this century (red dot). This shift will only be along the probability (return period) axis, as we consider the uncertainties in the consequence assessment for year 2100 too large to include them at this early planning

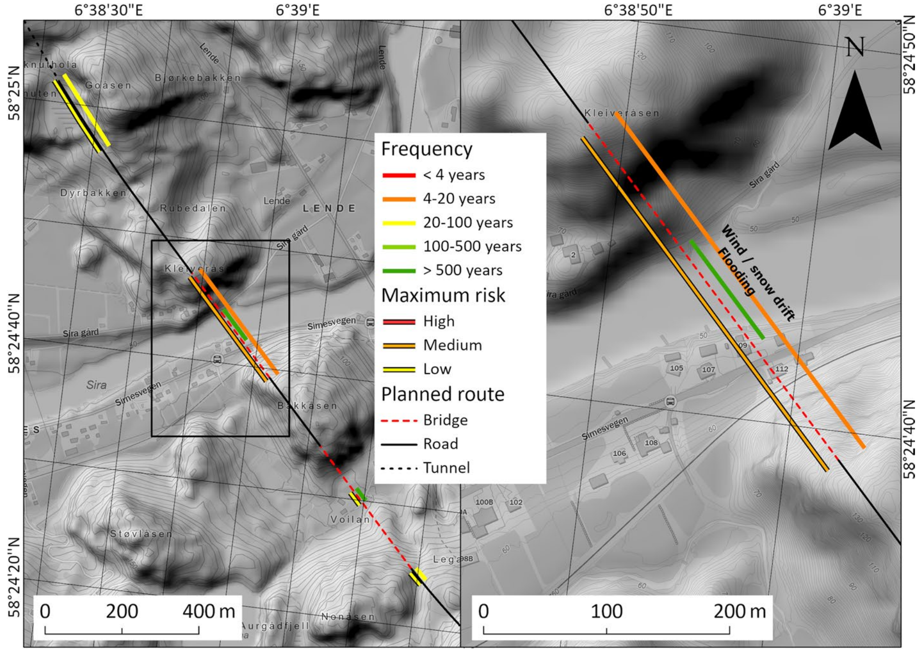

Fig. 7 Example showing the crossing of a large river, with potential hazards from flooding (green line) and wind w/snowdrift (orange line). In this example, wind hazard has higher probability (every 4–20 years) than flooding (less frequent than every 500 years). Even if a severe flood may lead to longer closed time, the higher probability makes the risk posed by the wind greater than the flood risk, and therefore plotted as the highest risk in this road section. The blown-up figure to the right also exemplifies how explanatory text appears when the map is zoomed

stage. The shift in probability towards the end of the century in some cases bring the risk up one class, mostly from low to medium, but also in some cases from medium to high.

The identified hazards reflect to a large degree the terrain and the geological conditions they are located in. Snow avalanche hazard is mainly restricted to roads at high altitudes and / or high latitudes. In the national susceptibility maps, snow avalanche hazard was widespread along the investigated routes. The optimization performed with the GIS tool limited this hazard to only very few locations in the lowlands, and after field inspection of these, the hazard at most of them was eliminated, with no need for further consideration in the final road design. River floods constitute a challenge all over the country, whereas quick clay slides cause the largest risk in areas below the marine limit in SE Norway and in low-lying regions of mid Norway. The probability of naturally triggered quick clay slides is low and primarily connected to erosion in streams and rivers. The consequences can, however, be large and lead to closures lasting for months because of complete destruction of the road in case of an event, and the need for extensive mitigation in a large area around the road. In areas of steep terrain, rock fall and debris flows- and slides can be frequent, but usually cause relatively little damage and short downtime for the road, and consequently mostly low to medium risk.

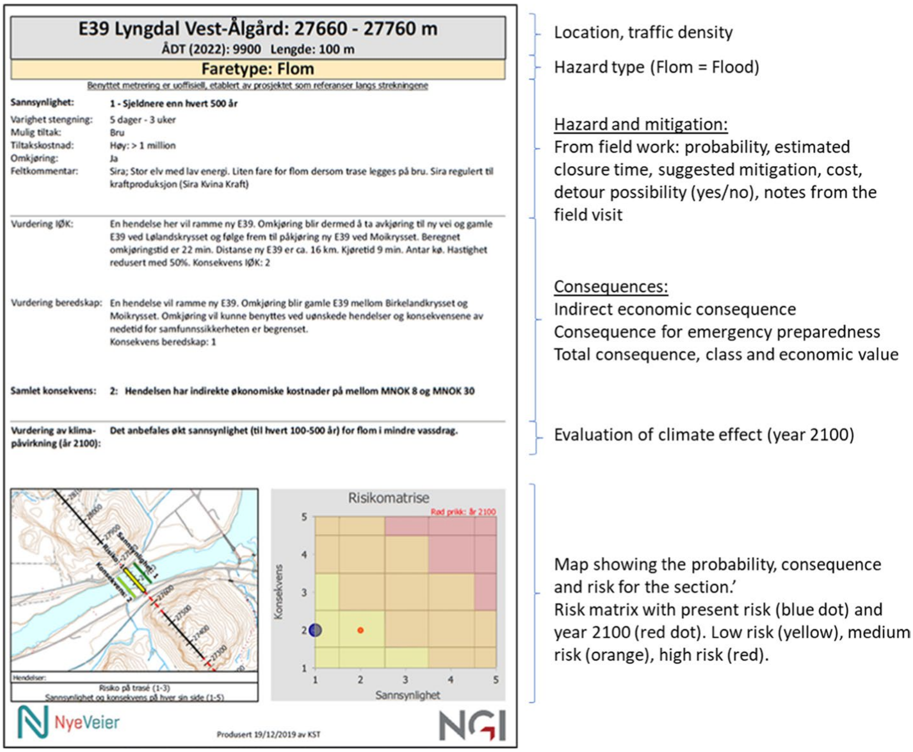

Fig. 8 Example of a 'fact sheet'. The text is in Norwegian, but the content is explained to the right

4 Discussion

The present study represents the first project in Norway to streamline early phase natural hazard assessment for road planning by combining available public data with run-out modelling on a GIS platform. Whereas there are many studies assessing the socioeconomic consequences of road closures, in Norway and internationally (e.g., Dalziell and Nicholson 2001; Tacnet et al. 2012; Toma-Danila et al. 2020; Norwegian Public Roads Administration—NPRA 2020) similar studies focusing on the hazard assessment are few and lacking in Norway. As economic consequences of natural hazard events on roads can be huge, investing in proper planning at an early stage can be profitable.

The method presented in this article is relatively coarse and certainly has a potential for further development. Combining the analyses with a more automated analysis of the consequences of road closures, such as that developed by Toma-Danila et al. (2020) and tested for seismic hazard in Bucharest, would be of interest. However, in the present work we had to balance the need for detail with processing speed and user friendliness, as the tool was to be installed at the client's systems for their own use in later road planning projects.

The main uncertainties and limitations in the method result from insufficient input data and limitations in the methods used, such as RF3D and NAKSIN for optimization of the hazard assessments. Furthermore, the choice of criteria for classifying the hazards is based on experience, which also introduces uncertainties. However, for the purpose of this study, early-phase planning of road construction, the assessments are considered to be of sufficient quality and accuracy.

The assessment of effects of climate change towards the end of this century has been a challenge and poses another uncertainty in both the method and the results. There is an uncertainty embedded in the emission scenarios and the climate models themselves. In Norway the emission scenario recommended by the Norwegian Climate Service Centre, and adopted in most climate adaptation work, is RCP 8.5, the ’business as usual’ scenario (IPCC 2014; Hanssen-Bauer et al. 2017). Following this, adding a ’climate factor’ of 20–50% has been recommended to estimate possible future events caused by precipitation (https://klimaservicesenter.no/kss/laer-mer/klimapaslag). For precipitation events with short duration, up to 3 h, Førland et al. (2015) recommended a factor of 40%, whereas Dyrrdal and Førland (2019) suggest more differentiated estimates, in which more precise estimates of expected design precipitation are included. For this early-phase assessment, the relatively coarse approach with fixed climate factor is considered sufficient. A more detailed approach, would be to address each site and hazard individually, using local weather statistics and prognosis from down-scaled climate models. However, this would have been considerably more time consuming, and would rather be a part of the detailed road design, after the final routing is decided.

As there is a direct link between precipitation and floods, as well as between precipitation and debris flows, these were the two hazard types for which we introduced a change in probability from now and until 2100. For the other hazards included in the study, the triggering factors are more diverse, and the probability was therefore kept as of today throughout this century, which certainly introduces additional uncertainties.

5 Concluding remarks

The present study is on the development of a quick and easy-to-use tool for an early assessment of potential natural hazards along at an early planning stage for new roads in Norway. The goal was to achieve the ability to select the optimal routing and minimize the need for costly mitigation measures. Norway has background data for all relevant natural hazards, from susceptibility maps covering the entire country and hazard maps in key areas. These data are utilized and optimized in a GIS- based assessment tool developed for the project and utilized on ca. 720 km of planned new highway routes. Main outcomes of the work include:

- Various optimizing techniques, combining data from various sources, were used to produce more realistic hazard zones than those that could be extracted from national susceptibility maps, which are conservative in nature. For snow avalanches and rockfall, this also included in-house developed and commercially available dynamic modelling tools.
- Validation through field inspections of ’hotspots’ mostly verified the hazard areas identified from the GIS analyses. Where modified, the hazard zones were usually more restricted after the field work.
- A rough climate analyses for the period until 2100, based on data from stations near the planned roads, resulted in increased probability for some hazards. Uncertainty was considered too high to change the consequences in 2100 compared to the present situation.

- A simplified consequence analysis, only comprising quantified indirect economic consequences and a qualitative assessment of consequence for emergency preparedness of a closed road, was combined with the hazards to constitute the risk analyses for each identified hazard segment.
- The deliverable was designed in close dialogue with the client and comprised a GIS tool with mapped elements and detailed interactive information as 'fact sheets' for each hazard segment.
- The GIS tool is relevant for all infrastructure, which can be delimited by a polygon, but is particularly well designed for linear infrastructure.

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Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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