Chapter

Cost-Benefit Analysis as a Basis for Risk-Based Rockfall Protection Forest Management

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Abstract

Mountain forests fulfill an important protective effect being the reduction of risk due to natural hazards. Knowing the value of this service is required to efficiently allocate financial resources in protection forest and risk management. In this chapter, we evaluate the protective effect of forests against rockfall at local and regional scale using a risk-based approach. We present a method to quantify rockfall risk under current forest conditions for a case study region along the Gotthard highway (Switzerland). Rockfall runout zones and relative frequencies were determined based on the energy line principle and occurrence frequencies were estimated based on inventory data. We quantified the protective effect of the current forest using a statistical approach and calculated the potential risk without forest. The risk reduction provided by the forest varies between 23 and 60% or 400 and 4500 CHF/(year.ha^{-1}). In a second step, we evaluated a single protection forest complex calculating its Net Present Value (NPV) for a time frame of 100 years based on the risk reduction and compared it to technical protection measures. The NPV of the current forest is positive, whereas protection measure variants including rockfall nets have a highly negative NPV. The results evidence the efficient risk reduction of rockfall protection forests. The presented methods allow for a differentiated procedure for protection forest planning at local and regional scale. A simple risk approach requiring a manageable data set enables practitioners to prioritize forest management. A more detailed economic analysis of protection forest efficiency finally facilitates the planning of protection forest measures at local scale.

Keywords: protection forest, rockfall, risk analysis, net present value, nature-based solution

1. Introduction

Forests provide important protection against rockfall in steep mountain terrain [1]. Thanks to this so-called Nature-based Solution, maintenance and installation costs of technical protection measures, such as dams or nets, are financially bearable or can even be avoided at many places due to the reduction of rockfall rebound heights and impact energies by previous impacts on trees [2]. Furthermore, protection forests fulfill additional functions in terms of wood production, biodiversity or water filtration [3]. Knowing the value of the protection service of mountain forests is key to efficiently allocate financial resources in forest and natural hazard management. A realistic valuation of the protective function of forests, however, can only be guaranteed if long-term costs and benefits are considered [4]. Often, the value of the protective function of forests is only qualitatively assessed or estimated based on general costs of replacing [5]. However, such approaches, only indirectly quantify the effect of forests on natural hazards and do not account for the potential damage prevented by the forest. A risk-based approach, on the other hand, allows for a translation of the physical effect of trees on the natural hazard process into monetary terms and thus a direct quantification of the avoided costs [6]. The latter are defined as the difference in risk with and without the protective effect of the forest [7]. To support decisions on risk prevention measures, including protection forest management or combinations of different types of measures, a cost–benefit analysis (CBA) is a method that provides standardized and quantified information on the efficacy and efficiency of the analyzed measures [8]. For a realistic long-term economic assessment of risk reduction measures, all costs and benefits must be adjusted to a common point of time, which can be done by calculating the Net Present Value (NPV), being the sum of all future expected benefits and costs discounted to today [9].

Valuing the protection service of the forest can facilitate the prioritization of protection forest management at local, regional and national scale. At local (e.g. slope) scale, a detailed quantification of the protective effect of a protection forest complex (i.e. one or multiple forest stands that protect against a natural hazard process) is required i) for the planning and comparison of risk prevention measures and ii) as basis for an efficient forest management. A valuation of the forest's protective effect at regional (e.g., valley) scale is important for the large-scale planning and prioritization of forest management measures.

In this chapter, we quantify the protective effect of forests against rockfall at local and regional scale using a risk-based approach. We present a simple method to estimate risk and the risk reduction provided by forest at regional scale and then do a profound economic valuation of a single protection forest complex based on a cost–benefit analysis and compare it to technical protection measures. The methodological approaches are presented based on a case study region along the Gotthard highway in Switzerland, where rockfall events frequently end up on the mountain side driving lanes.

2. Risk-based regional protection forest planning

As a basis for prioritization of regional protection forest planning, we determined rockfall risk under the current forest conditions for a case study region along the Gotthard highway based on a simple risk approach. We subsequently used a statistical model to determine the risk reduction potential of the forest in monetary terms (**Figure 1**). The study region comprises a section of the Gotthard highway A2 in Switzerland between Gurtnellen and Wassen with a length of ~5.5 km (Canton Uri; **Figure 2**). This highway section is continuously endangered by rockfall from cliff faces that stretch stepwise from approx. 750 to 2000 m a.s.l. There are several sections (in total ~2.2 km) that are protected by galleries from rockfall and other natural hazard processes.

2.1 Methodology

Rockfall release areas were determined using a slope threshold angle of 50°. We estimated rockfall runout zones based on the energy line principle, using the ELine tool [10], which calculates potential runout cones for each rockfall start cell. In case of multiple start cells, overlaying runout cones allow for a quantification of the reach probability of blocks in a specific cell. Based on these modeled reach probabilities, we calculated a relative reach probability along the highway by defining three probability classes ("low",

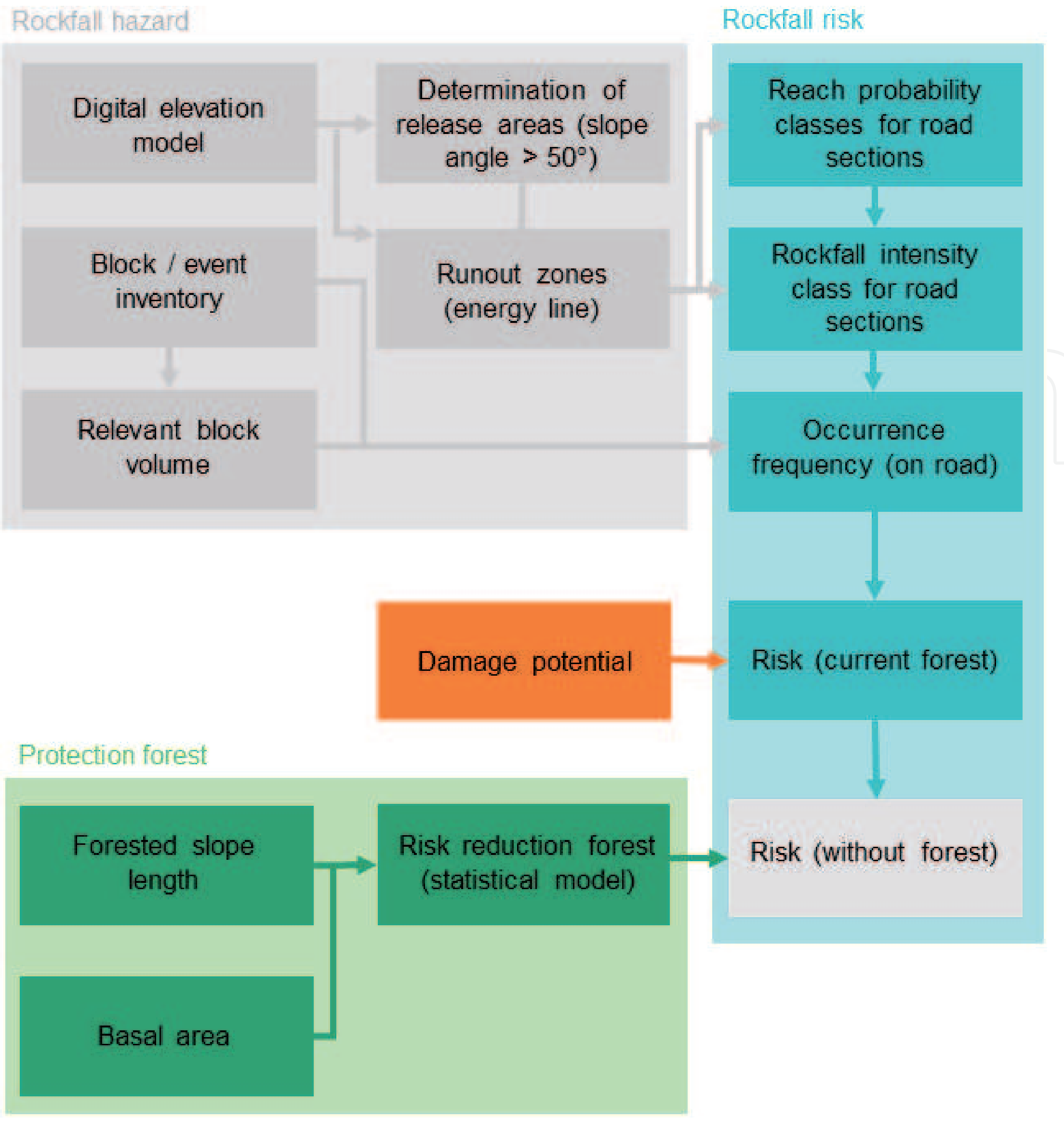

Figure 1.
Flow chart of the methodology for the risk-based evaluation of the protective effect of forests at regional scale.

"medium", "high"). We assumed an energy line angle of 30° for the total study area and additionally calculated runout zones with an angle of 35°, which did not result in changing reach probability classes. The runout zones were determined for a block volume of 2 m^3, which regularly reaches the highway. The occurrence frequency of blocks >= 2 m^3 on the highway was determined based on inventory data from the national road office [11]. The catalog contained 31 events of one or several blocks that reached the highway or stopped in nets just above in 30 years. We therefore assumed in this study an occurrence frequency of 1 rockfall event (>= 2 m^3) per year reaching the highway (galleries excluded). This frequency was then weighted for different highway sectors according to the calculated reach probability classes. We then calculated the yearly rockfall risk (CHF. $yr.^{-1}$) for each section based on [11] and accounted for the damage types "direct impact" (only for regular fluid traffic conditions), "collision" (with rock deposits on the road or other vehicles), "infrastructure damage" and "road closure after a hazard event" (see also [12] for a detailed description of risk calculation). The variable values used for the risk calculation are presented in **Table 1**. Sectors with galleries were not considered in the risk analysis. We used vulnerability values for objects and persons for the intensity classes according to [11]. The monetary value of the element at risk was calculated as the sum of the standardized object value [11] and the monetized value of persons (given as 6,600,000 CHF $person^{-1}$ in Switzerland; [14]).

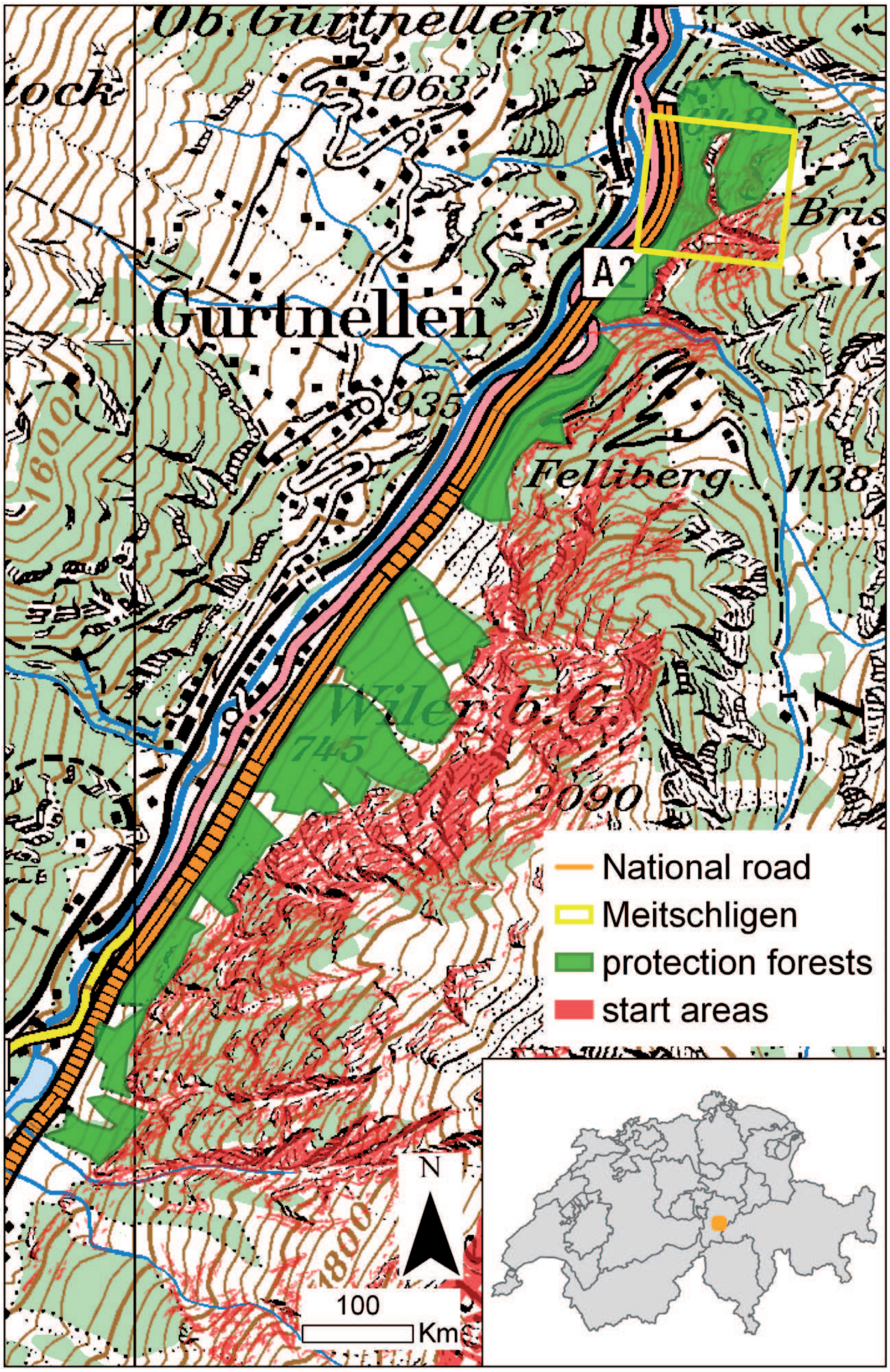

Figure 2.
Study region along the A2 Gotthard highway with protection forest complexes and release area and the local case study site in Meitschlingen.

In order to estimate the risk for the unforested slope, we determined the risk reduction potential of the current forest based on a statistical approach proposed by [13]. The model calculates the relative reduction (in percent) of the rockfall frequency and intensity depending on the basal area of the forest, the forested slope length, the block volume and the horizontal forest structure (e.g., gaps, clustered, …). We applied it to homogenous forest areas determined based on the forested slope length. Since no regional data on forest structure (e.g. cantonal forest inventory) was available, we assumed a basal area of 15 ("bad forest condition") and 30

Variable	Value	Unit	Source
Mean daily traffic (MDT)	22,500	vehicles.day^{-1}	www.astra.admin.ch
Indicated maximum speed on the highway section	100	km.h^{-1}	Field observation
Forest intervention costs (harvesting + preparation, road maintenance)	110	CHF.m^{-3}	[13]
Revenue from wood sales	75	CHF.m^{-3}	idem.
Net installation costs (200 kJ)	1,200	CHF.m^{-1}	[4]
Net installation costs (500 kJ)	1,500	CHF.m^{-1}	idem.
Net installation costs (5000 kJ)	4,500	CHF.m^{-1}	idem.
Discount rate (mean value last 30 years in CH)	2	%	idem.
Road closure costs	87,000	CHF.day^{-1}	[11]
Costs of human life	6,6 Mio	CHF	[14]

Table 1.
Values and their sources of variables used for the calculation of risks and the NPV.

("good forest condition") m^2.ha^{-1}, respectively, covering a realistic range determined based on the forest data available from the local case study (see section 3). We only calculated frequency reduction, since we used intensity classes in the risk analysis and a direct translation of the forest effect is not applicable. Based on the derived risk without forest, we were able to assess the risk reduction provided by the forest per road section in monetary terms (CHF.yr.$^{-1}$).

2.2 Results

The risk on the total section for the current situation with forest amounts to ~330,000 CHF.yr.$^{-1}$ (**Table 2**). More than two thirds stem from direct impacts and 25% from road closure after hazard events. In other words, one fatality due to direct impacts is expected every 30 years on average. The risk reduction provided by the forest varies between 15 and 55% under good forest conditions and 0 and 30% under relatively bad forest conditions (i.e., regarding rockfall protection), respectively (**Table 2**). This results in a yearly risk reduction between 800 and 2,500 CHF and 0 and 1,000 CHF, respectively, per ha protection forest (**Figure 3**). Based on the calculated risk reduction, the total risk would increase to ~470,000 CHF.yr.$^{-1}$ without forest.

Section	Total risk with forest [CHF.yr.$^{-1}$]	Risk reduction forest (range) [%]	Total risk without forest (range) [CHF.yr.$^{-1}$]
1	13,800	0	13,800
3	19,000	0–15	19,000–22,300
5	52,200	0–16	52,200–62,400
7	113,700	30–55	157,000–208,700
9	90,300	0–21	90,300–114,600
10	40,800	0–15	40,800–48,100

Table 2.
Calculated total risk with and without forest for the road sections (see ***Figure 3****; without galleries) and risk reduction provided by the forest (reported as range for a forest with a basal area of 15 or 30 m^2.ha^{-1}).*

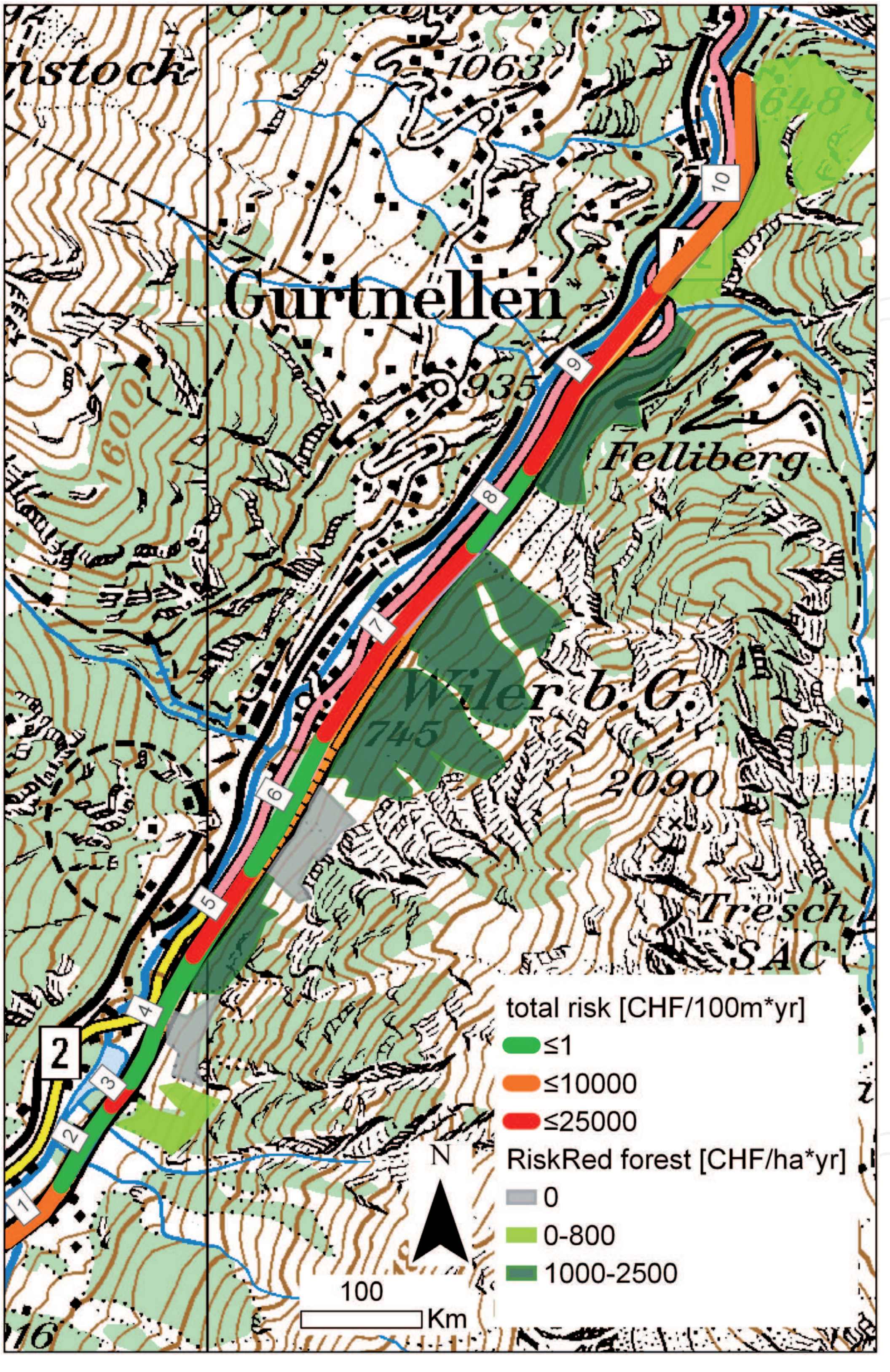

Figure 3.
Total risk with the current forest along the considered highway section, and risk reduction provided by the protection forest complexes.

3. Risk-based protection forest assessment at local scale

As a basis for comprehensive forest management at local scale, we economically assessed the performance of a particular protection forest complex in the study region and compared it to structural protective measures and a combined approach

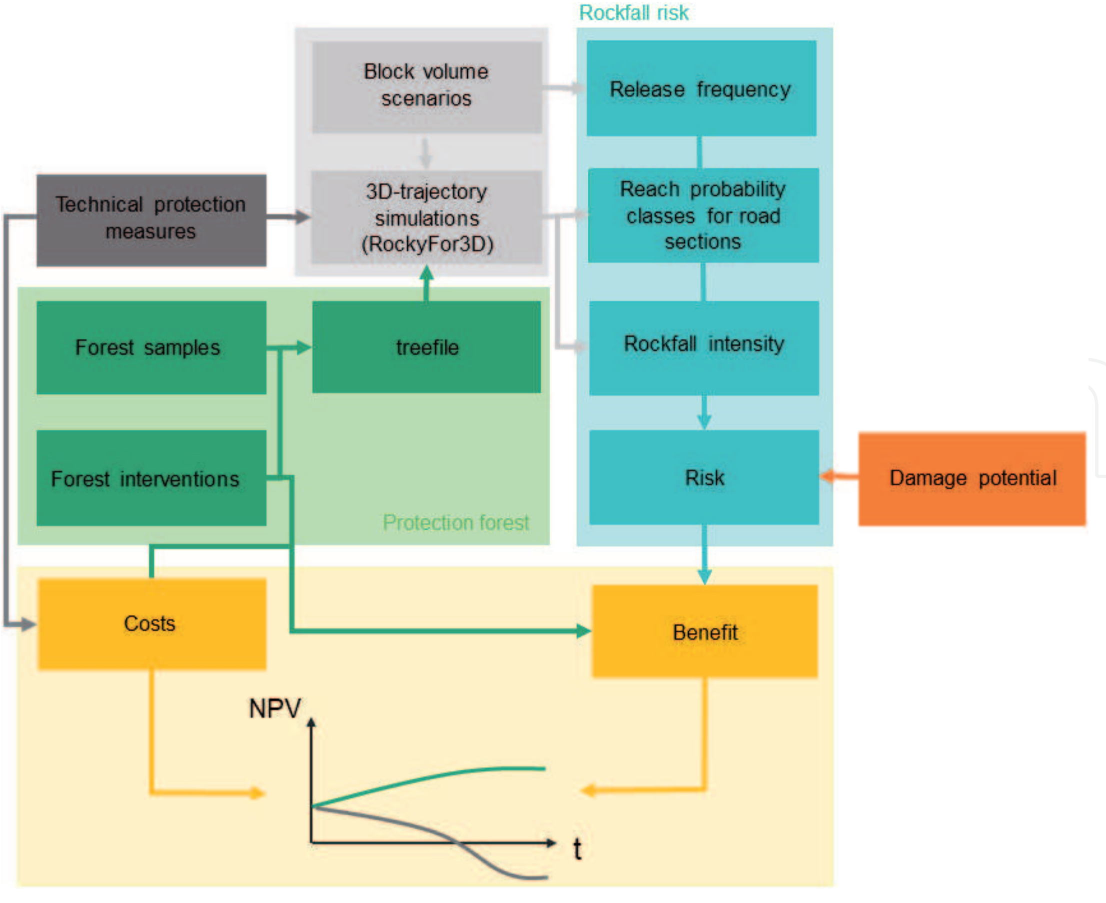

Figure 4.
Flow chart of the methodology for the economic evaluation of a protection forest at local scale based on the calculation of the net present value (NPV).

(**Figure 4**). The chosen site is the Gotthard highway section between Meitschligen and Stotzigwald (**Figure 2**).

3.1 Methodology

We determined the net present value (NPV) of the current forest with a management scenario of gap cuttings that aims at promoting regeneration (variant 1) and compared it to i) a combination of variant 1 and the currently installed flexible nets (variant 2), and ii) only currently installed flexible nets, without trees (variant 3). To determine the benefit (i.e., risk reduction), we compared the risk with a given protection measure variant with the situation without protective measures (no trees and no nets). This is the "baseline" variant.

To calculate the risk for a given protection measure, we modeled the propagation of single rectangular blocks with a maximum volume of 1, 2 and 15 m^3 with the three-dimensional rockfall trajectory software Rockyfor3D [15]. The topography was defined by a digital elevation model (DEM) with a resolution of 2 x 2 m and soil types and roughness were mapped in the field. Forest stands were delineated with orthophotos and field inventory plots. For each stand, we measured trees with a stem diameter at breast height (DBH) larger than 8 cm in randomly sampled plots of 20 by 20 meters. All trees were recorded. Subsequently, the mean DBH, the standard deviation of the DBH, the number of stems per hectare and the proportion of coniferous trees were calculated for each stand. Rockyfor3D uses this data to create a forest model consisting of individual trees with their position and DBH. We assumed that every 20 years, 25% of the total standing volume would be removed

Variant	Total risk [CHF.yr.$^{-1}$]	Difference with baseline variant [CHF.yr.$^{-1}$]	NPV [1000 CHF]	Benefit–cost ratio [–]
"Baseline" (no trees, no nets)	30,647	—	—	—
1 (current forest/no nets)	25,493	5,154	110	1.79
2 (variant 1 + current nets)	23,464	7,182	-1,314	0.24
3 (variant 1 + maximum nets)	19,743	10,904	−10,814	0.05
4 (current nets, no trees)	29,690	956	−1,469	0.04

Table 3.
Total risk per year, risk reduction (difference to baseline variant), NPV and benefit–cost ratio per protection measure variant for the case study site in Meitschligen.

by using cable crane lines and lateral regeneration gap cuttings of 20 by 30 m. We removed the trees in the intervention gaps from the generated forest model and simulated rockfall trajectories and calculated the change in risk reduction after a forest intervention. The current mean standing volume per ha is 575 m^3 (i.e., almost 6000 m^3 on 10.4 ha). The net costs of a single forest intervention add up to 165,808 CHF (intervention costs) – 113,098 CHF (revenue of wood sales) = 57,710 CHF.

The rock type is gneiss and we defined its density as 2700 kg.m^{-3}. The used block volumes were defined by a geological engineering consulting firm commissioned by the Swiss Federal Roads Office FEDRO for a hazard analysis in 2010. The attributed onset probabilities (detachment probability at the rockfall cliffs) were 0.067 (10-year recurrence interval – 1 m^3), 0.023 (30-year recurrence interval – 2 m^3), 0.007 (100-year recurrence interval – 15 m^3) and 0.003 (300-year recurrence interval – 15 m^3). The difference between the 100- and 300-year recurrence interval was determined by the number of individual blocks that descend the slope, which was randomly set to 2 to 5 blocks for the 100- and 4 to 8 blocks for the 300-year recurrence interval. The 10-year recurrence interval was a fixed single block scenario, while the 30-year recurrence interval was a randomized 1 to 3 block(s) scenario.

Upslope along the highway we placed a virtual control screen allowing for recording all relevant data for the risk calculation (number of passed rocks, energy distribution, passing height distribution). For each defined block volume and variant, we simulated 1000 trajectories per release cell.

As for the large-scale study, our risk calculation was based on [10] and accounted for the same damage types. We then calculated the NPV, based on the defined recurrence intervals, following:

$$NPV = \sum_{t=1}^{100} \frac{\left[I(w) + I(rr)\right] - \left[O(n) + O(m) + O(f)\right]}{\left[1+i\right]^t}$$

Where I(w) = revenue from wood sales (CHF); I(rr) = risk reduction (CHF); O(n): costs for installing flexible nets (CHF); O(m) = operation and maintenance costs for the flexible nets (CHF); O(f) = costs for forest interventions (CHF); i = discount rate; t = year.

Values for the variables we used for the calculation of risks and the NPV, are presented in **Table 1**. We here focused on the risk calculation on the highway only.

3.2 Results

The total risk per year (sum of the risk for the four defined rockfall recurrence intervals) for both the baseline and protection forest variant is given in **Table 3**. The current forest (without nets) provides a risk reduction of 5,154 CHF.yr.$^{-1}$. In combination with nets, the risk reduction is increased up to 10,900 CHF.yr.$^{-1}$. However, only the NPV of variant 1 (current forest without nets) is positive. All variants with nets have a distinctly negative NPV due to the high investment and maintenance costs of the rockfall nets.

4. Discussion and conclusions

The here presented large-scale risk assessment evinced a substantial risk reduction between 500 and 5000 CHF.(ha.yr)$^{-1}$ of the current protection forest along the Gotthard highway. Without the forest, risk would increase up to 150%. When additionally considering the reduction of rockfall intensity (and not only rockfall frequency), risk could even increase more. The proposed methodology allows for a simple estimation of risk and the protective effect of the forest and thus serves as an ideal basis for a rough prioritization of protection forest management at regional scale. Assuming that silvicultural interventions in a protection forest complex are required approximately once per 20 to 30 years and that they cost 12,500 CHF per hectare and intervention (maximum federal contribution to protection forest intervention in Switzerland; [16]), protection forest management is with yearly costs of ~500 CHF highly efficient. For this, however, a basal area of minimum 30 m^2.ha^{-1} is required. How much a forest reduces risk depends strongly on its structure and state. A low tree density and a short forested slope length can critically reduce the protective capacity [13, 17]. Thus, spatial data on forest structure are required to satisfactorily predict the risk reduction of the forest. In this study, such data was partially missing why we calculated risk reduction for a range of the basal area. Furthermore, the block volume strongly influences the protective effect of forests. This effect was greatly simplified by considering rockfall risk generalized for block volumes >= 2 m^3.

For a risk-based planning of protection forest management at local scale, a more detailed approach is necessary. The calculation of the NPV of a protection forest complex based on its risk reduction allowed for a long-term economic valuation of the protection service and a comparison to technical measures and combined approaches. Although the variant forest + nets provides the highest risk reduction, its NPV is highly negative (−1 million CHF over a period of 100 years) and its benefit–cost ratio is 0.05. Variant 1 (forest with management and no nets) is the only one with a positive NPV. This variant is also the only one with a benefit–cost ratio larger than 1. Comparing variant 1 to variant 4 (nets without forest) shows a substantial increase of the efficacy of the forest-nets combination with an increased risk reduction of more than 400%. Hence, combining forests and nets can significantly increase the risk mitigation capacity of nets.

Finally, the results from the regional study are in good agreement with the detailed analysis on local scale (i.e., the Gotthard highway section between Meitschligen and Stotzigwald used for the local scale study corresponds to 60% of the highway section nr. 10 in the regional study). On regional scale, we calculated a risk of 40,800 CHF.yr.$^{-1}$ and a risk reduction of the forest of 7,200 CHF.yr.$^{-1}$ for a forest with a basal area of 30 m^2.ha^{-1} in the respective section. In the local study, we revealed a risk of 25,400 CHF.yr.$^{-1}$ and a risk reduction of 5,200 CHF.yr.$^{-1}$. This indicates that the on large scale estimated risk reduction of the forest covers a realistic range.

The presented methods allow for a differentiated procedure for protection forest planning at different scales. At regional scale, the combination of a simple risk approach and a statistical model enables practitioners to determine the risk reducing effect of the forest as basis for prioritization of forest management measures. Currently, prioritization is mainly done on the basis of Eisenhower's Urgency/Importance principle, where urgency is determined by the state of the protection forest and importance on the provided protection. The latter however, is based on a rapid qualitative expert appraisal, which can be more objective based on the method proposed in this chapter. The method requires mainly i) elevation and land cover data for a rough estimation of rockfall runout and intensities; ii) basic data on the damage potential; and iii) spatial data on forest cover (i.e. basal area and forested slope length). At local scale, more detailed data on rockfall frequency and runout as well as on forest structure and the costs and benefits of protection forest interventions are necessary to conduct a detailed economic evaluation of the protection forest service. Such an evaluation allows practitioners for planning efficient (both economically reasonable and sufficiently effective) protective measure variants that take protection forests, including the required silvicultural interventions, into account. For additional risk-based evaluation approaches of forests' protective effects against gravitational natural hazards see chapters [18–20] of this book.

Conflict of interest

The authors declare no conflict of interest.

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