Chapter

Flood Protection by Forests in Alpine Watersheds: Lessons Learned from Austrian Case Studies

Gerhard Markart, Michaela Teich, Christian Scheidl and Bernhard Kohl

Abstract

This chapter highlights the influence of mountain forests on runoff patterns in alpine catchments. We discuss the forest impact at different spatial scales and bridge to the requirements for an integrated natural hazard risk management, which considers forest as an efficient protection measure against floods and other water-related natural hazards. We present results from a wide range of research studies from Austria, which all reveal the runoff-reducing effect of forest vegetation in small and medium-size catchments (< 100 km^2). Forests also contribute to runoff reduction in heavy rainfall events in macro-scale catchments (> 100 km^2), e.g., by reducing surface runoff and delaying interflow, but above all by stabilising slopes and therefore reducing bedload transport during major runoff events. To avoid that forests become a hazard due to enhanced driftwood release, managing of steep riparian slopes for a permanent forest cover ("Dauerbestockung") is a basic prerequisite. Often protective effects of forests are impaired by man-made impacts like dense forest road networks, insensitive use (e.g., false design of skid roads, compacting machinery, forest operations during adverse weather on wet and saturated soils), and delayed or omitted reforestation and regeneration. Flood risk management in mountain regions should include Ecosystem-based Disaster Risk Reduction measures, with particular emphasis on sustainable and climate change-adapted management of protective forests. This will require integral and catchment-based approaches such as comprehensive management concepts coordinated with spatial planning, and verifiable, practicable and correspondingly adapted legal guidelines as well as appropriate funding of protective forest research to close the existing knowledge gaps.

Keywords: mountain hydrology, floods, landslides, protective forest, risk management, runoff

1. Introduction

Mountain forests and their soils serve an important role in preventive flood protection by ensuring that rainwater is retained over large areas during potential runoff formation, which has been demonstrated for medium-sized flood events in numerous studies (e.g., [1–5]). In contrast to grasslands, forest vegetation can reduce average catchment discharge by higher rainfall interception, evapotranspiration, free soil pore volume and soil hydraulic conductivity, which also influence near-surface and subsurface runoff (e.g., [6, 7]; for definitions see **Table 1**).

These mitigating effects are however limited by either the intensity of a precipitation event or by the soil water storage (SWS) capacity of the forested catchment (**Figure 1**; for definition see **Table 1**). If SWS capacity is high, surface runoff from forested sites remains significantly below the surface runoff from comparable sites without forest vegetation. In case of precipitation intensities typical for triggering flood events, forest's interception capacities are reached rapidly, and evapotranspiration for such short duration and high intensity events can be neglected, so that esp. subsurface runoff from forest areas may approach amounts from unforested sites – with a corresponding time delay. In addition, extensive deforestation can

Terms and symbols	Definition
Antecedent soil moisture content (ASMC) [Vol%]	Degree of prefilling, i.e., water content of the soil before a precipitation event (determines the free available storage volume)
Soil hydraulic conductivity [m sec^{-1}]	Ratio between the velocity vs. a hydraulic gradient in porous media (e.g., soils) indicating the permeability of the medium
Surface runoff coefficient SRC [−]	Ratio of surface runoff vs. precipitation
Runoff coefficient at discharge constancy RC_{const} [−]	Runoff coefficient when the discharge from a given area stops increasing, which is derived from rain simulation experiments
Soil pore volume [Vol%]	Empty pore space in the soil, that is filled with air and/or water
Soil water storage (SWS) capacity [Vol%]	Total amount of water that can be stored in the soil
Specific discharge [m^3/sec.km^2]	Discharge per unit area of a watershed

Table 1.
Definitions and symbols of used technical terms.

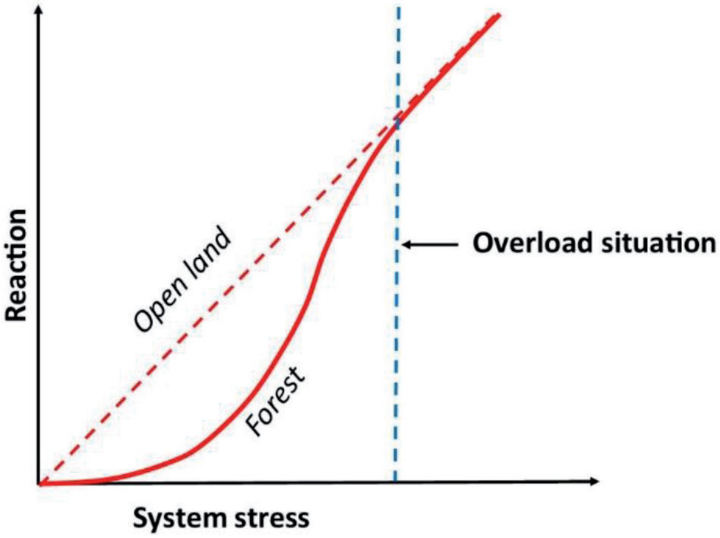

Figure 1.
Impact of forest on runoff formation compared to open areas depending on precipitation supply (amount and duration of event = system stress or load). Reaction = surface and subsurface runoff, which sometimes also results in (shallow) loose sediment landslides. Overload situations, which trigger flood events, occur when the capacity limits of interception and available SWS are exceeded – With high shares of subsurface stormflow, return flow and saturation overland flow (from: [8], Modified).

lead, especially on Leptosols, to a solum that is losing organic matter, due to enhanced decomposition, which eventually results in less water absorption capacity. Thus, at sites where SWS capacity is naturally (e.g., shallow soils) or anthropogenically reduced, effects of forests on surface runoff formation are limited and an "overload situation" (i.e., a flood event) can occur much earlier, especially if soils are already saturated.

Besides the positive effects of forests on surface runoff, also near-surface and subsurface runoff are influenced by forest vegetation by allowing quick water flow along roots, and through channels formed by decayed roots. Concentrated subsurface flow is found in forest especially in soils with limited permeability or damming layers, i.e., when soil layers with ample porosity overlie hardpans or solid rock. For example, subsurface flow velocities of 5 to 35 m d^{-1} were measured in spruce- and beech-dominated forest stands on moderately inclined pseudogley soils [9], and intermediate flow velocities of 500 m d^{-1} are likely in forest soils with near-surface macro-pores induced by roots, fissures, or shrinkage cracks [10, 11]. That is, due to the macro-porous structure and propagation pressure of inclined forest soils, full saturation is hardly possible since rainwater infiltrating on the upper slope can force stored water out of the lower slope and into the watercourse. Under the same soil conditions, surface runoff and subsurface flow in unforested open land is generally higher caused by a lower proportion of rapidly permeable pores, soil compaction or dense root systems e.g., from *Nardus stricta* or some *Festuca* species, which have a hydrophobic effect ("Strohdach-Effekt") [12].

Forest and land use management can influence the timing and volume of water delivered to stream channels via various discharge routes such as surface runoff, but also the flow paths themselves [13]. Clear cuttings, for example, lead to increased runoff, especially in alpine catchments that are highly sensitive to precipitation change [14, 15]. The Austrian Service for Torrent and Avalanche Control (WLV) and the Provincial Forest Services have therefore started programs to improve protective forests, and to initiate and maintain high-altitude afforestation after the Second World War. These measures were also implemented to reduce the high costs for new technical protection structures and to enhance the limited effects of existing "grey" (e.g., concrete) infrastructures downstream [16]. However, browsing of ungulate game species and grazing livestock often counteract forest's protective functions and effects in many Alpine countries [17].

2. Forest's protective effects from slope to catchment scales

2.1 Slope scale

On steep side slopes of torrents, protective effects of forests are key for soil conservation since significantly higher surface runoff and erosion can be expected on bare ground and in scarcely vegetated areas during heavy rainfall events. Targeted afforestation can greatly improve the hydrological response of such sites [18, 19]. For example, rainfall simulation experiments (where water is constantly applied over a certain area and time) on clear cuttings yielded surface runoff coefficients (RC_{const}; for definition see **Table 1**) up to 0.8, in contrast to RC_{const} of up to 0.5 in young spruce stands [20]. Moreover, findings from the ITAT4041 project BLÖSSEN [7] show that even in catchments with a low proportion of forested area, forest vegetation reduces runoff clearly on slope and sub-catchment scales (**Figure 2**). Results from other studies indicate that secondary forests (i.e., forests, which develop through natural succession after disturbance of primaeval forests) have lower SRCs and lower surface runoff velocities than single-species plantation forests or grassland (e.g., [23]).

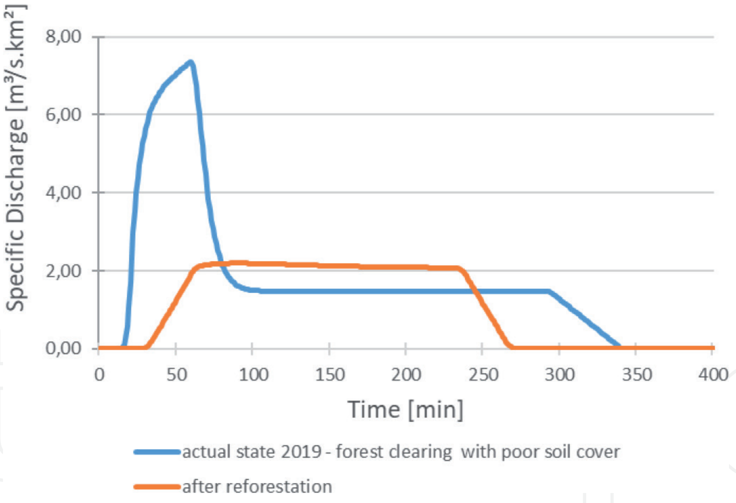

Figure 2.
Modelled specific discharge with ZEMOKOST [21] for a forest clearing with scarse ground vegetation cover and after reforestation of this site at Istalanzbach catchment in Tyrol, Austria, during a torrential rainfall event (58,3 mm precipitation in 60 min) yielded low surface runoff from reforested areas (orange) and high runoff peaks on forest clearing (blue) with poor ground cover (from [22]). Results were validated with data from rain simulation experiments.

Additional mechanical loads, e.g., from heavy and long-term grazing, can significantly worsen the surface runoff behaviour (amount and timing) in forested sites leading to similar surface runoff patterns as in grazed grasslands [12]. Comparisons of rainfall simulation data collected in twelve catchments in Austria with different types of land use and cover, including ski runs, showed that (forest) soils are strongly affected by compaction and/or grazing [24]. Levelled medium to fine textured forest soils are most affected when they are tilled during wet weather conditions and immediately as well as continuously compacted by vehicles or grazing. Consequently, they have very high runoff coefficients. However, forest road cuts in general largely disturb slope-scale surface runoff and cause erosion [25, 26] (**Figure 3**). In addition, high proportions of the uphill slope's surface and subsurface flows as well as the runoff from the road enter the receiving watercourse much faster than from undisturbed slopes [28].

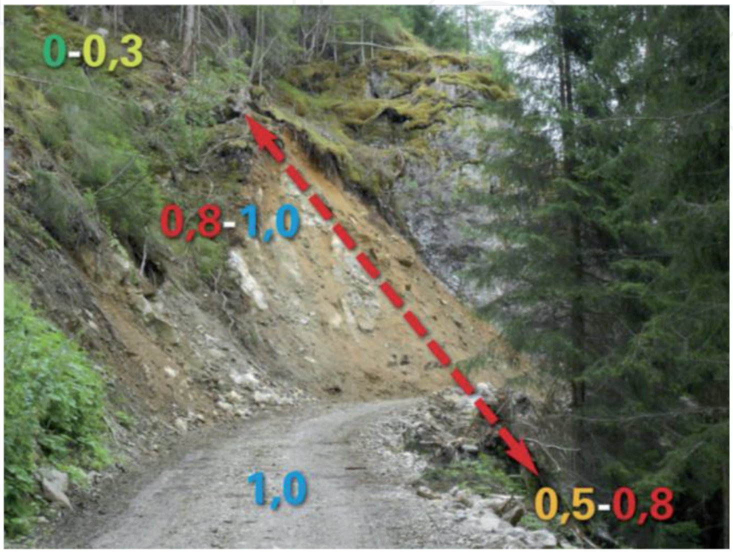

Figure 3.
Typical distribution of runoff coefficients at constant discharge for a slope segment with a forest road cut, representing results from rainfall simulation experiments. On average, RC_{const} between 0.8 and 0.9 can be expected for the entire width (red dotted line) and 1.0 for the road over a width of at least 5 m (from [27]).

Unfortunately, anthropogenic changes repeatedly outweigh the positive effects of measures to improve the hydrological function of protective forests. To partially compensate for 1 ha of disturbed and levelled forest soil, a minimum area of 5 ha of downslope forest must be optimised e.g., from $RC_{const} = 0.2$ to $RC_{const} = 0.1$. In fact, compensation is much more difficult and costlier, because runoff from roads and road outlets is concentrated in concave depth contour lines down slope and flow distances of hundreds of meters downhill are necessary to entrain such concentrated surface runoff at least partially [27].

2.2 Micro-catchment scale (< 10 km^2)

Peak flows in forested catchments (< 10 km^2) occur with a significant delay and are generally lower compared to unforested areas [22, 29]. This was also proven in a modelling experiment on the hydrological impact of land management changes implemented by the WLV between 1953 and 2003 in the Finsing Valley in Tyrol, Austria [3]. The largely forested control catchment of the Hundsbach (0.9 km^2) experienced little changes over the studied period. In the Taleggbach catchment (1.7 km^2), the area of alpine pastures was reduced by 75% after 1953 by afforestation measures, and conditions of forests were improved, e.g., by abandonment of forest pasture or closing of gaps by afforestation. Simulations of precipitation and runoff relationships (P/R) with the P/R model ZEMOKOST [21] showed no change in the discharge for the Hundsbach between 1953 and 2003 (**Figure 4**). In contrast, a significant reduction of the peak discharge by more than 50% was modelled for the Taleggbach catchment after the hydrological optimization measures became effective, i.e., the increased surface roughness (c) in the improved protective forest significantly reduced surface runoff velocity. Simulation results were validated by field data collected in 2007. In small mountain catchments, afforestation and forest structure improvements can considerably reduce surface runoff as also shown for other mountainous areas, e.g., in Serbia [29].

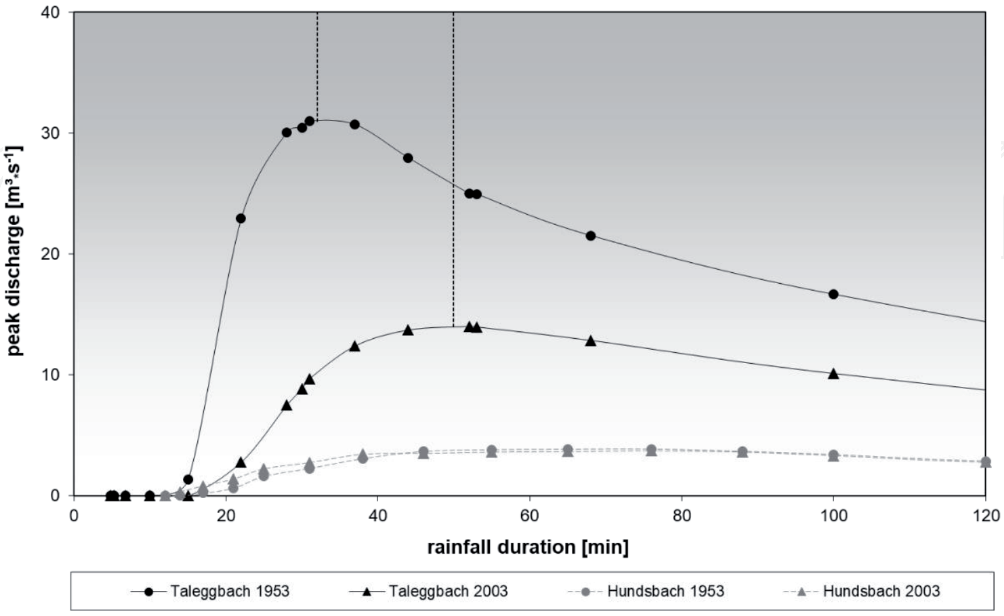

Figure 4.
Peak discharge modelled with ZEMOKOST [21] for torrential rainfall events of different duration from the Hundsbach and Taleggbach (Finsing Valley, Tyrol, Austria) before (1953) and after hydrological optimization measures were effective (2003) in the Taleggbach catchment, where critical event rainfalls lead to the highest peak discharge after 30 min in 1953 compared to 50 min in 2003 with a 50% discharge reduction (from [3], modified).

2.3 Meso-catchment scale (10-100 km^2)

We also assessed the hydrological impact of land management improvements (improvement of forest structure, extensive afforestation at high altitudes, reduction of pasture areas, etc.) and local deterioration with ZEMOKOST [21] for the entire Finsing valley (46.6 km^2) [30]. For the land use and management status of 2007 the critical design event rainfall (84 mm) lasted 64 min with a peak discharge of 122 $m^3 s^{-1}$. In 1953, the critical rainfall duration was 71 min with a peak discharge of 113 $m^3 s^{-1}$ (**Figure 5**). Given this small difference in runoff behaviour, one could assume that the elaborate and costly measures did not have an adequate runoff reducing effect. However, land use and management additionally changed since 1953 due to deteriorating measures over large areas by converting meadows to pastures, constructing ski slopes, and sealing soils for touristic infrastructure. Without the improving land management measures by the WLV, peak discharge would have been about 160 $m^3 s^{-1}$ in 2007 (see **Figure 5**). Therefore, forest vegetation controls runoff volume and timing also in mesoscale catchments.

Specifically, on the meso-catchment scale, sealing or grading and compaction of forest soils have devastating impacts on runoff and flood formation, which can only be compensated to a limited extent by improving protective forests located below or onsite [30]. In France, for example, deforestation in the headwaters of mountain rivers was blamed for extensive flooding in the valley floors in the late 18th century. The argument of increased runoff caused by deforestation was soon generalised and applied to the whole Alpine region. The so-called "Deforestation paradigm" [31], was born particularly due to the massive lobbying by forest associations. In Switzerland and other regions of the Alps, flood protection principles developed in the 19th century remained unchanged until the second half of the 20th century [32]. This was only changed by the emerging environmental debate and the occurrence of new severe flood events, despite massive defence and afforestation measures in the catchment areas [33].

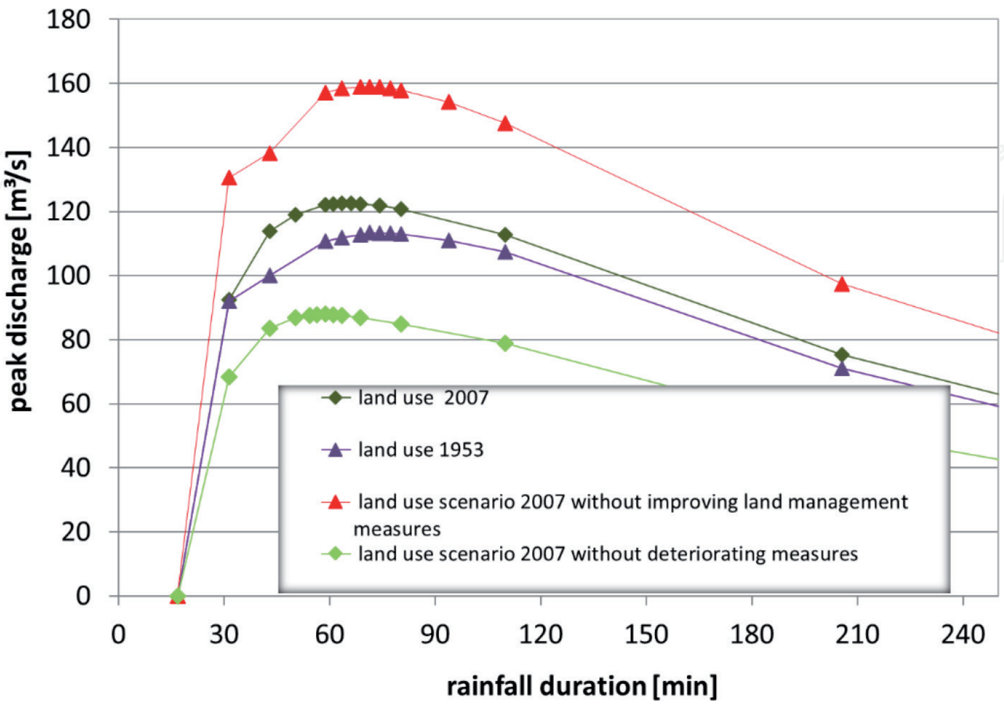

Figure 5.
Computed effects of land use and management on peak discharge in the Finsing Valley, Tyrol, Austria (from [31], modified).

2.4 Macro-catchment scale (> 100 km^2)

The retentive and runoff-reducing effect of forest vegetation during persistent and heavy rainfall events over large areas appears to be small, according to various studies (e.g., [8, 34, 35]); Forests have, however, an area-wide retentive effect on runoff formation, not only because of rainfall interception, but also because forest soils generally show better infiltration characteristics [36]. According to Wahren et al. [37] "the effectiveness of land-use changes in flood protection is limited but the biggest potential of decentral flood retention lies in the sum of effects (infiltration, pre-event soil moisture, soil storage, surface roughness, reduced erosion risk etc.)", however, "... the exact role of land use change in modifying river floods is still elusive..." [38].

During the devastating flood event of 22–23 August 2005 in Western Austria, up to 214 mm precipitation was measured in 24 h at Au in Vorarlberg. Almost area-wide indications for intensive surface runoff such as turned-over grass and traces of transported fine sediment were found on alpine pastures in the event analysis. Many shallow landslides indicated additional intensive subsurface flow above less permeable soil layer in the pastures. Surveys in the surrounding forest areas did not show any evidence of increased surface runoff, besides some temporary flow in small channels and runoff reactions from karst systems. The number of shallow landslides in forest covered areas was very low [39].

Ultimately, we repeatedly forget the multifunctionality of protective forests in technical discussions about forest's impact on runoff and, therefore upon flood events in macro-scale catchments. Even during continuous or longer heavy rainfall events, adequately managed protective forests provide a stabilising effect on slopes and reduce the transport of solid material by lateral mass movements and thus the potential for mud- and debris flows.

3. Reducing mass movements vs. enhancing driftwood release

In addition to surface runoff reduction, forests can also influence erosion, transport, and deposition of coarse sediment and therefore fluvial bedload along streams as well as mud- and debris flows. In many cases, spreading of root systems contributes significantly to the stabilisation of slopes, preventing shallow landslides [39–41], and potentially reducing material supply for bedload transport. This effect may gradually decrease after the loss of forest cover and delayed reforestation, which can lead to a dramatic increase in subsurface flow up to 400% within the first four years and a loss of the soil-stabilising effects of the root system within 15 to 20 years after forest cover loss [39] (for details see chapter [42] of this book).

Especially in steep alpine catchments, lateral erosion processes are related to mass movements such as landslides or avalanches, which can entrain and transport coarse and fine sediments and downed trees into streams [43, 44]. Through the release of driftwood (already lying large woody debris or debris downed during the flood event) and in-channel wood (transported during previous flood events), protective forests can also enhance danger for outburst flooding by clogging grey infrastructure, increasing damage from mud- and debris flows and causing dam breaks [43].

Several approaches to assess the potential damage driftwood can cause have been recently developed and applied in protective forest management (e.g., [43, 45, 46]). For example, the danger of potential driftwood release was explicitly included when modelling fluviatile hazard processes to identify forest areas in Switzerland that protect an acknowledged damage potential within the project SilvaProtect-CH [47]. GIS-based approaches to assess driftwood potential were developed for Bavaria, Germany [46], and Tyrol, Austria [48].

Figure 6.
Seigesbach catchment in Tyrol, Austria, after the heavy rainfall event from 7 to 8 June 2015, which released approx. 200,000 m^2 *of solid material. Previous driftwood management adjacent to the torrent and large area salvage-logging following windthrow resulted in less driftwood, but more landslides were released from these areas.*

To reduce the potential of driftwood release from old and mature forest stands along torrents, a more frequent harvest interval should be considered. During a disastrous precipitation event in the 4 km^2 Seigesbach catchment area in Tyrol, Austria, on 7–8 June 2015 approximately 200,000 m^3 of solids were discharged, but almost no driftwood was entrained in the channel. An analysis of the event showed that large areas of the catchment were unforested caused by previous windthrow and salvage-logging [49], and that regeneration was largely absent due to high pressure from ungulate browsing. However, the loss of the forest cover and the absence of a viable regeneration led to higher incidences and greater extents of landslides compared to the catchment area with undisturbed forest (**Figure 6**). Therefore, slopes with high driftwood potential should be managed for a permanent forest cover ("Dauerbestockung") and larger trees should be removed at shorter intervals. This approach still contradicts the current management practice, where clearings are recommended at distances of 1–1.5 tree lengths from the stream channel [50].

4. Integrated risk management and climate change

An analysis of almost 11,000 catchments in the Eastern Alps has shown that an increase in forest cover by 25% reduces the probability of torrent-related natural hazards by 8.7% ± 1.2% [5]. Thus, measures to maintain, improve and restore the hydrological buffering effect of forests are important for reducing natural hazard risks and for climate change adaptation. The problem, however, is to quantify the effectiveness of specific measures in the socio-ecological context [51]. "Risk management, communication and planning of forest ecosystem services are complicated by uncertainty, insufficient information or information of poor quality, limited cognitive capacity and time, along with value conflicts and ethical considerations" [52]. Thus Calder et al. [53] proposed an improved approach to river basin and flood management, combining land use management in watersheds with land use planning, technical measures, flood prevention and emergency management in the affected floodplains, which corresponds to the goals of Ecosystem-based Disaster Risk Reduction (Eco-DRR) [54] (for further information on Eco-DRR see chapter [55] of this book).

Traditional approaches of flood risk management must be adapted to changing conditions due to population growth linked to high area consumption and increased soil sealing, large-scale changes in land use and climate change. On sites not affected by drought, or extreme temperatures and/or substrates, targeted protective forest management should aim to achieve increased resistance and resilience of the forest vegetation against natural disturbances (e.g., windthrow, bark beetle outbreak) and climate change without reducing the protective effects against natural hazards [44, 56, 57]. Therefore, future flood risk management and disaster risk reduction requires more integrated, site adapted and catchment-based approaches [58], i.e., a better-balanced mixture of technical and ecosystem-based protection measures [59]. Near-natural flood protection measures such as small-scale forest management, timely reforestation, afforestation, avoidance of mechanical stresses to forest soils and the sustainable management of non-forested sites can significantly reduce volume, timing, and velocity of rapid runoff and shallow landslide disposition in small Alpine catchments [12, 27, 39, 60]. Such measures, therefore, can mitigate the potential impact of flood events and extend the time for disaster preparedness.

Climate change and associated increases of natural disturbances such as windthrow and insect infestations will alter the effectiveness of protective forests in preventing shallow landslides [61] (see also chapter [62] of this book). Landslide risk will increase and, thus, optimising forest management regarding climate change and natural hazards, including hydrological and geomorphological hazards, is a necessity [63]. Current protective forest management practices mainly view ecological conditions and site units as static but adapting to climate change requires a more dynamic approach [64].

The following steps are essential to ensure that findings from scientific research will be applied in catchment area management and to improve public acceptance of forest as an effective and cost-efficient protection measure against natural hazards [65]:

- Development of practical guidelines with generally understandable vocabulary,

- Adapted legislation and by-laws at national and local levels to apply and implement guidelines consistently and comprehensibly,

- Increased financial support for more applied research on forests and water as the basis for practical guidelines [53].

Based on results from the ITAT4041 project BLÖSSEN on "Effects of delayed reforestation on natural hazards", a stakeholder workshop, extensive field investigations, experiences of foresters in the test areas and results from other field surveys in 40 catchment areas as well as an extensive literature review, a first "Guideline to optimise the hydrological effect of protective forests" for mountainous regions in the Eastern Alps was developed [27]. This guideline is an essential basis for future protective forest management and implementation of technical measures, e.g., by the Tyrolean Forest Service.

Integrated risk management should ensure the highest possible long-term protection from natural hazards [66]. Consequently, the instruments for spatial planning should be implemented in such a way that construction of new green or grey infrastructure does not adversely affect natural hazards and vice versa. This can only be achieved through efficient coordination and communication between all involved entities such as public authorities, forest services, and landowners during the planning phase. Such a participative process guarantees the acceptance of optimal protection measures and the efficient allocation of financial resources in flood risk and watershed management [67].

In addition, research results, management strategies or planned measures should be communicated target-oriented to a broader audience of stakeholders using a common vocabulary and modern information and communication technologies [68]. In this context the "Protective Forest Action Programme" passed the Austrian Council of Ministers on 22 May 2019. The program identifies 35 specific activities to improve the current situation and to ensure the sustainability of protective forests in Austria [69].

Conflict of interest

The authors declare no conflict of interest.

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