Pilot Study Report 1

Adapted forest management in Austria

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WORKING PAPER

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SEE Project OrientGate

A structured network for integration of climate knowledge into policy and territorial planning

Thematic Centre 1

Forestry and Agriculture

Pilot Study 1

Adapted forest management in Austria at LTER Zöbelboden

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1. Introduction

How will climate conditions look like in future in Europe? Which challenges do we have to tackle with in “forestry” in connection with guaranteed water supply? Which adaptation needs to climate change are indispensable?

Since about 50% of Austria´s drinking water resources are originating from the karst areas of the Northern and Southern Limestone Alps, which are mainly covered by forests, it is of great importance to analyse comprehensively the potential impacts of climate change as well as forest management on the quality and quantity of drinking water resources in these areas. Due to a short residence time of water the filtering and transformation capacity of vegetation and soil are very important for the quality of karst spring water. But which climate change induced impacts on forests can be expected in future? The scientists determine still many uncertainties. The reaction of forest ecosystems to climate change can be very subtle or strongly altered by disturbances like bark beetle or fungi infestations among certain tree species, wind-throw events or forest fires. Erosion and increased sediment input as well as nitrate leaching into the karst system are following and thus influence the quality of drinking water. Also the possible increase of strong precipitation events due to climate change can impair water quality. But these impacts can be balanced until a certain degree by increased forest stability. Therefore the establishment of adequate silvicultural concepts and measures, which focus on the enforcement of forest stand stability, is essential.

In this context the Forest Department of the Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management is developing together with scientific institutions, different public and private organisations a new Austrian forest programme for the protection of respectively against water, its package of measures is part of the funding catalogue in the frame of the new period “Rural Development 2014-2020”.

2. The OrientGate Project

The OrientGate project aims to coordinate climate change adaptation efforts in South Eastern Europe (SEE) by building a lasting partnership between producers of climate data and decision makers who use climate data in national, regional and local planning. In order to encourage the involvement also of local communities the existing information is made more available and accessible. A web-based data platform will provide the gained experiences within this project beyond the project duration as it will be connected to the EU Clearinghouse on Climate Adaptation.

As many countries in SEE are vulnerable to the impacts of climate change OrientGate will foster better understanding of climate risks and identify concrete adaptation measures.

The OrientGate partnership comprises 21 financing partners, 9 associated partners and 3 observers, covering 13 countries (see Figure 1). Partners have different roles and can be grouped into three main categories: scientific institutions, national hydrometeorological services and institutions responsible for policy planning. This project is led by the Euro-Mediterranean Centre on Climate Change (CMCC).

To analyse specific adaptation needs on different sectors (forestry, agriculture, urban settlements, hydropower, water resources in coastal areas as well as wetlands) 6 pilot studies (see Figure 1, blue dots) are carried out within three “Thematic Centres” in coastal areas as well as in rural and urban areas. Each case study will cover monitoring, risk and adaptation needs assessment and the transfer of lessons learned into policies and planning.

Figure 1: Map of the OrientGate pilot areas (REC, 2014)

The Thematic Centre “Forestry and Agriculture” focuses on the assessment of agro- and silvicultural adaptation issues of management and policy in the context of climate change and its impact.

The Forest Department of the Federal Ministry of Agriculture, Forestry, Environment and Water Management (BMLFUW) was responsible for the management of this “Thematic Centre”. By means of two Pilot Studies, one focusing on climate change adaptation in forest of the Austrian Northern Limestone Alps (LTER Zöbelboden, see Figure 1, orange dot), the other on agricultural adaptation in Romania (Covasna and Caracal agricultural area), recommendations for a more sustainable land use considering climate change were derived.

In the frame of the Pilot Study 1 “Adapted forest management at LTER Zöbelboden” experts of the BMLFUW respectively of the Federal Research and Training Centrefor Forests, Natural Hazards and Landscape(BFW) were investigating in close cooperation with the Environment Agency Austria (Umweltbundesamt) and the Department of Forest and Soil Sciences of the University of Natural Resources and Life Sciences (BOKU) the test area ‘LTER Zöbelboden’ “(Link: http://www.umweltbundesamt.at/leistungen/netzwerke/oekosystem_monitoring/) in the ReichramingerHintergebirge (Northern Limestone Alps). On this site the effects of air pollutants on the whole ecosystem have been investigated in detail already since 1992. Thus, this 90 hectare large forest stand is one of the best studied karst forest ecosystems in Austria and even in Europe.

For each Pilot area, adaptation strategies and guidelines were elaborated in close cooperation with important regional stakeholders so that a practical implementation can be guaranteed. In Pilot Study 1the Forest Service of Upper Austria was closely involved as an associated partner within the project. Built on this expertise, jointly prepared training courses in the Pilot area offered forest landowners respectively managers and farmers an opportunity to become acquainted with goal oriented silvicultural and agricultural measures necessary for the adaptation to climate change. For the international workshop in each Project area a broader audience – also beyond the national border - was invited to effectively improve capacity building and awareness raising.

3. The Pilot Study 1–Executive Summary

Nearly 22 % (about 18.000 km^2) of Austria’s total area consist of carbonate rocks. About 15 % of the whole territory is karstified. In classic definition karst areas consist of soluble rocks (e.g. limestone, dolomite, gypsum, anhydrite, halite etc.) und they are characterized by largely absence of surface drainage. Karst catchments provide half of the water supply for the Austrian population. Due to the often short residence time, the filtering and transformation capacity of vegetation and soil are very important for the quality of karst spring water. Large karst areas are located in the Limestone Alps, where in the montane and subalpine life belt forests are the dominating land cover. Forest management and climate change directly or indirectly exert impacts on water supply, both in terms of quality and quantity. In order to safeguard water resources, forest management should focus on maintaining a continuous forest vegetation cover, on minimizing disturbance, and on the prevention of soil degradation.

The Environment Agency Austria runs a long-term ecosystem research site in the “Kalkalpen” national park (LTER Zöbelboden, N 47°50'30", E 90 14°26'30"). The forest types of LTER Zöbelboden are representing major forest types of the Northern Limestone Alps in Austria, in particular mixed spruce-fir-beech forests. The core of Pilot study 1 was the development of model based scenarios of climate change effects on water runoff amount and quality. The scenario results were discussed with local authorities, forest managers, and policy makers and optimal adaptation strategies for forest management were defined.

We give here a summary on the main results. The details are presented in several annexes:

- A detailed review on adaptation of forest management strategies to maintain high water quality in the Northern Limestone Alps and relevant policy implications (Annex 1)
- A manuscript describing the plot-scale modelling study to assess climate change impacts on nitrate leaching at LTER Zöbelbdoen (Annex 2)
- The report on rain event sampling at LTER Zöbelboden, which was the basis to calibrate a catchment scale hydrological model (Annex 3)
- A manuscript describing the catchment scale model VarKarst and its application to assess the windthrow effects on karst groundwater quality (Annex 4)
- A description of the complementary model study at LTER Zöbelboden with the 3D-CMCC Forest Ecosystem Model (Annex 5)
- A description of the sensitivity indicator “Water protection-Forest-Index” (Annex 6)
- List of Indicators used for modelling (Annex 7)

3.1 Main results

Forests play an important role as they stabilize the fragile soil and humus horizons which dominate the Northern Limestone Alps and, when managed appropriately, keep water pollution at a low level. A paradigm among forest managers is that forests should be close to the tree species diversity of the potential natural forest community and a continuous cover forest management system should be applied in order to guarantee a long-lasting and sustainable protection of the drinking water resources in karst areas. The high diversity of tree species according to the natural forest communities provides a robust basis for the stability and resilience of forest stands, both under current climate and also under expected climate change. In the past and even under current forest management, the establishment of homogeneous Norway spruce (*Picea abies* Karst.) plantations created forest stands, which are vulnerable to wind throw, bark beetle infestations or snow damages and therefore accelerated erosion rates and collateral turbidity impacting drinking water supply. These forests are managed with clear-cuts or shelterwood cuts in order to maximize economic return. When adapting the management in water protected areas of the Northern Limestone Alps, forest management should follow “Best Practices” for drinking water protected areas. The main focus is on the prevention of clear-cut management and the subsequent establishment of a continuous cover forest management system. Also the transformation of Norway spruce plantations into forests according to the potential natural vegetation which mostly are mixed forests with a dominance of European beech (*Fagus sylvatica* L.) is of crucial importance. Additionally, management should minimize felling of a larger proportion of trees by the application of a maximal timber yield percentage since contamination of water with nitrate and other elements (e.g. increased turbidity and microbiological contamination) may occur and soil organic matter may erode.

3.1.1 Nitrogen deposition acts in addition to climate change

At present, nitrogen pollution seems to be the most widespread threat for groundwater in the Northern hemisphere. Though contamination of drinking water with nitrate is usually attributed to fertilization of crops and grassland, an excess input of atmospheric nitrogen from industry, traffic and agriculture into forests has caused reasonable nitrate losses. Although monitoring results show that nitrate concentrations in karstic springs in Austria are rather low, the Northern Limestone Alps are areas of particularly high nitrogen deposition so that high loads of nitrate reach the groundwater. However, combined effects with climate change can be expected because the nitrogen cycle is tightly linked to climate and to any disturbances that disrupt the tree canopy such as clear-cuts, wind-throw and bark beetle infestations. Expected longer periods of dryness in summer time will intensify these problems.

3.1.2 Warmer summers and wetter winters

Climate change in the Northern Limestone Alps will exert warmer temperatures and a precipitation change, which is rather uncertain however, may increase in winter in form of more rain and decrease in summer.

3.1.3 Less karst water in summer and more in winter and spring

Runoff may decrease in the summer season by 10 to 50 % and, depending on the scenario, will increase in winter by a maximum of 40 %. The latter is not only an effect of increasing precipitation but also snowmelt which occurs already during winter or earlier in spring.

3.1.4 Forest management determines the contamination of drinking water with nitrate

Trees take up nitrogen and lose nitrogen via above and belowground litter fall. Furthermore, trees control the microclimate of soils, which, in turn, determines nitrogen turnover. Tree harvest hence exerts a strong control to nitrogen cycling but also to the loss or accumulation of soil organic matter. Forest management interventions may cause severe nutrient and humus losses from the soils, which may lead to a partial loss of soil functions. Clear-cut disrupts the nutrient cycle so that nitrate is mobilized and washed out from the soils. Typically these effects are strongest during only a few years after the event. However, reasonable nitrate leaching occurs during this phase and may contaminate the groundwater. The L-DNDC model showed that seepage water nitrate concentrations reached > 80 mg/l after a total clear-cut whereas without disturbances nitrate concentration is mainly < 20 mg/l. Tree species choice also influences nitrate leaching. Coniferous trees such as Norway spruce intercept more nitrogen from the atmosphere and these forests show higher nitrate concentration in the seepage as compared to mixed or deciduous forests. Forest management concepts like single tree or group selection cuts, or continuous cover forestry and mixed forest stands are an option to prevent clear-cut phases and its negative consequences.

3.1.5 Climate change has both positive and negative effects to water quality

Climate changes have both positive and negative effects to nitrate loss from managed forests. Peak nitrate concentrations in the seepage during clear-cut and thinning increased under all scenarios. Also during understorey reinitiation in clear-cut and shelterwood systems nitrate leaching was higher as compared to the current climate. This is due to a retarded understorey tree development as a consequence of increasing water stress in summer and nutrient deficiency. Nitrogen is therefore taken up by trees less efficiently, transpiration is lower and higher infiltration enhances the transport of nitrate below the rooting zone and subsequently into the groundwater. At the altitude of the study area of 950 m a.s.l. a warmer climate will be beneficiary for the growth of Norway spruce. In L-DNDC simulations, the enhanced growth of spruce trees under the climate scenarios outweighed the stem wood biomass accumulation under the current climate and, consequently, nitrate loads to the groundwater were lower. Under all management options however, climate change lowered cumulative nitrate losses over full forest rotation periods. This improvement was highest in continuous forest cover management while conventional management subdued the positive effect of climate change to nitrate loads leaving forest soils.

3.1.6 Climate driven forest disturbances may have a strong effect on water quality

Indirect effects of climate change on forest ecosystems, such as wildfire, wind-throw and insect outbreaks, may be more severe than direct effects because soil organic matter and related pollutant losses are severe after disturbance. Climate change was as important as forest management for the increase in forest area burnt, wind and bark beetle damage in Europe during the last decades. Climate change and forest disturbances owing to insect infestations are closely correlated. Wind-throw and biotic disturbances increase runoff peaks, soil erosion and nitrate leaching. Moreover, long-lasting soil organic matter degradation may occur after forest disturbances, particular in the Northern Limestone Alps with their shallow soils. Usually, seepage water undergoes natural attenuation in the epikarst and the karst conduits by e.g. immobilization in biofilms and mixing with older water. At LTER Zöbelboden, nitrate concentration in the spring-water remained below 10 mg/l since 1992 and did not exceed 15 mg/l after wind throw of about 10% of the catchment.

3.1.7 The effects of changes in climate extremes

Though predictions as to whether or not extreme climate events will change are still uncertain, the related effects should be addressed in assessment studies but are still extremely challenging. Pollutant transport in karst areas is often driven by strong runoff events when potential pollutants spoil the drinking water.

3.1.8 The use of climate indicators

The used climate indicators refer to the infiltration of precipitation in the soil and subsequent drainage through the karst mountain. Since these are the main processes driving pollution in karst areas, total annual precipitation (PRCTOT) is a useful indicator. In particular snow accumulation (SWE) is tightly linked to elevated pollutants loss to the drinking water in spring and is also highly sensitive to climate changes. On the other hand, indicators reflecting changes in extreme events (R50mm, CDD) are less useful since current models are highly uncertain with regard to such changes. Forest sensitivity indicators, such as the water protection functionality index (WPFI) play an important role due to the high impact of forest management practices to forest functions (e.g. drinking water effects).

3.2 Conclusions and lessons learned

During the 19th century until today temperature has risen by almost 2°C in the European Alps. In the study area, which is representative for the Northern Limestone Alps in Upper Austria, a further increase of 2-5 °C is predicted until 2100, with highest increase in the summer. The expected precipitation changes (up to approx. 20% increase in winter and the same range of decrease in summer), though predictions as to the latter are still rather uncertain, might cause drier summers and wetter winters and early springs. The used climate indicators are well suited to show these changes.

The Northern Limestone Alps are characterized by shallow soils which are vulnerable to nutrient loss and erosion once the forest cover is damaged. Since many settlements in the region depend on high quality drinking water supply stemming from forested headwaters, forest functions such as water retention and filtering of pollutants have to be maintained and even restored where necessary.

The forests of the Northern Limestone Alps will be affected by further climatic changes. Norway spruce is the most abundant tree species in Austria but is also the most vulnerable to additional temperature increase. Many forest sites at lower to middle altitudes will not be suitable for Norway spruce in the future. Also in the present the homogeneous spruce plantations created at natural beech forest sites can be regarded as highly vulnerable and instable.

At higher altitudes however, Norway spruce might even experience growth stimulation. However, a particular risk in all spruce forests is the increase of bark beetle infestations, very probable driven by climate warming, on large spatial scales causing both damage to forest ecosystem functions and less economic return for forest owners.

Forest management affects water quality in various ways. The prevalent Norway spruce management has led to even-aged, homogeneous forests. These forests are less resilient than mixed conifer-deciduous forests and therefore face stronger and more frequent disturbances. Moreover, the usual management of Norway spruce forests is done with clear-cuts or shelterwood-cuts potentially causing a contamination of water pollution. With regard to nitrate, but most probably also regarding turbidity, expected climate change will enhance the negative effects of these management interventions to water quality. An adequate management option for optimizing water protection, which is particularly important in water protected areas, is therefore the creation of mixed forest stands which includes a wider range of naturally occurring tree species and the establishment of a continuous cover forest management system. Those two goals are part of an overall Best Practice catalogue for forest management in drinking water protected areas. Particularly in the light of expected climate change effects to forests, an adaptation towards such a management system is recommended.

A number of constraints exist as to the adaptation of forest management in water protected areas. Since in many cases even-aged Norway spruce forest plantations predominate, the transformation into mixed forests is a long-term task. Educated personnel have to be built up, the appropriate planning instruments have to be made available and a monitoring and evaluation system has to be established in order to guarantee a continuous adaptation of forest management. Secondly, different user interests exist in headwater areas which might counteract continuous cover forest management. In major parts of the forests in the State of Upper Austria tree regeneration is suppressed significantly due to browsing damages caused by elevated wild ungulate populations. Hunting management is therefore as important as forest management if adaptation to climate change has to succeed. Economic constraints are the third issue. The establishment of mixed forests and a continuous cover forest management system leads to less economic return for the forest owners. This is a constraint against adaptation, particularly if the headwaters are not owned by the community so that different interests compete against each other. Hence in many cases forest management adaptation towards an optimization of water quality needs a compensation payment to the forest owner. Though financial subsidies can improve the adaptive capacity to climatic changes of the forestry in water protected areas, it is still very important to raise the awareness among forest owners, headwater managers and the local water works in the communities.

Uncertainty as to the magnitude of climate change effects is significant. Adaptation will therefore be a dynamic process rather than a single decision. The availability and the usage of the most recent modeled climate pathways would have clear benefits. However, this is novel to most local forest managers and regional forest services. Firstly this data has to be made available in an understandable way and in a meaningful resolution. Secondly, training is necessary as to how climate scenario data can be used efficiently. As an example, the forest service of Upper Austria uses brochures which provide clear management guidelines for forest owners using rather simple climate scenarios for different regions. The provision of more detailed indicators could be a next step. Last but not least, research has to accompany adaptation in order to gain continuous knowledge as to the best adaptation measures.

The importance of the drinking water protection should be more emphasized within the relevant forest related legislation. As an example, the land-use regulation or forest management aspects in the area of drinking water protection and conservation zones should be determined and strictly observed. Also in the Austrian Federal Forest Act binding legislative rules have to be defined specifically for drinking water protected areas. As several studies already documented, that clear-cuts have a severe influence on water quality, the restrictions of clear cuts by the Forest Act (below 0,5 ha or below 2 ha, if the regional forest authority gives its permission) are too weak to ensure source water protection.

4. Annex 1

Adaptation of forest management strategies under climate change to optimize water supply in karst regions of the Northern Calcareous Alps

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4.1 Abstract

Karst catchments supply almost half the Austrian population with drinking water. Large karst areas are located in the Calcareous Alps, where forests dominate the montane and subalpine vegetation belts. Disturbances, partly a consequence of climate change, may diminish the water storage, filtering and buffering capacity of forest ecosystems, thereby threatening the continuous provision of pristine water. Safeguarding water supply from karst regions therefore requires the adaption of forest management strategies. The comprehensive review describes stability- and vulnerability-indicators of karst systems: from tree species, the vadose zone, in particular soils to karst water. An up to date review of forest management and disturbance effects upon water quality is the basis for suggested adaptive forest management strategies in view of water protection. The strategies are set in context within legal frameworks, like the EU-Water Framework Directive and the Austrian Forest Law Act, and other European, national and regional strategies and the national subsidy programme 'Forest for Water'.

Keywords: karst, water, forest management

4.2 Introduction

Nearly 22 % (about 18.000 km2) of Austria's total area consists of calcareous rocks. About 15 % of the whole territory is karstified (Trimmel, 1998). In classic definition karst areas consist of soluble rocks (e.g. limestone, dolomite, gypsum, anhydrite, halite etc.) und they are characterized by largely absence of surface drainage. Karst catchments provide half of the water supply for the Austrian population. Due to a short residence time of part of the karst water in the system, in particular in limestone karst aquifers, the filtering and transformation capacity of vegetation and soil are of ultimate importance for the quality of karst spring water. Large karst areas are located in the Calcareous Alps, where in the montane and subalpine life belt forests are the dominating land cover. Forest management and climate change directly or indirectly affect forest dynamics and thereby exert impacts on water supply, both in terms of quality and quantity. In order to safeguard water resources, forest management should focus on maintaining a continuous vegetation cover, on minimizing disturbance, and on the prevention of soil degradation.

The aim of the present publication is to provide an overview about the vulnerability of forest-covered karst systems, to highlight forest management effects on water supply in karst areas and to derive best management strategies in view of rising temperatures, climatic extremes and elevated nitrogen deposition rates. Finally the strategies are discussed in the context of national and international legislation, conventions and programmes.

4.3 Vulnerability and vulnerability indicators

In order to evaluate the integrity and resilience of forested karst systems, the distribution and specific properties of vegetation, soil, epikarst and karst water are discussed briefly.

4.3.1 Vegetation

The karst systems in Austria are mainly covered by forests in the montane and subalpine zone and include heath and grassland areas in the alpine and subalpine zone. Also of major significance are rock or gravel sites, which spread over all altitudinal zones. Vegetation plays an important role as it stabilizes the fragile soil and humus horizons and in the case of forests it also reduces rock fall and avalanche dynamics. A paradigm among forest managers is, that sites with potential vegetation cover should be covered with the potential natural vegetation in order to enable the water protection functionality for a given site. Forests are a focus of interest within the thematic frame of the OrientGate project.

Vulnerability of dominant tree species in the calcareous Alps to climatic stress and related biotic disturbance

Within the Austrian forested karst systems a variety of tree species can be found. Among the dominant tree species there dominate European beech (Fagus sylvatica), Silver fir (Abies alba), Norway spruce (Picea abies), European larch (Larix decidua)and dwarf pine (Pinus mugo). Also wide spread Sycamore maple (Acer pseudoplatanus), ash (Fraxinus excelsior), common white beam (Sorbus aria), Austrian pine (Pinus nigra var. austriaca), Scots pine (Pinus sylvestris), sessile oak (Quercus petraea) and rowan berry (Sorbus aucuparia) can be found. More infrequently distributed occur downy oak (Quercus pubescens), Wych elm (Ulmus glabra), yew (Taxus baccata), willow species (e.g. Salix eleagnos) or holly (Ilex aquifolium). There occur other tree and shrub species, which together with the above mentioned contribute to the high diversity of forest communities within the Calcareous Alps of Austria. It has to be highlighted that the potential diversity of tree species within the variety of natural forest communities is an excellent basis for the stability and resiliency of forest stands, both under current climate conditions and also under climate change (Koeck and Hochbichler, 2011; see also chapter 4.5 “Concepts of vulnerability mapping”).

In contrast, the establishment of homogeneous Norway spruce plantations on various different forest sites of the Calcareous Alps created in many cases instable forest stands, which are highly vulnerable to wind throw, bark beetle infestations or snow damages. Especially under climate change scenario conditions these homogeneous forest stands could become even more vulnerable to natural disturbances.

The tree species ash (Fraxinus excelsior) faces currently a threat. The ash disease caused by a fungus (Halmschlager and Kirisits, 2008) destroyed already many ash trees in the Calcareous Alps and still diminishes the vitality of this tree species. How this disease will develop and how ash will face this threat remains still unclear. Also further tree species are currently under threat, like e.g. Wych elm (Ulmus glabra) which is also endangered by a fungus transmitted by a bark beetle species.

The fact that some tree species show a high vulnerability towards various natural disturbances underlines the importance of mixed forest stands. The instable Norway spruce plantations in many cases will have to be transformed into mixed forest stands within drinking water protected areas (DWPA) in order to ensure the water protection functionality of the forests. The tree species distribution should be based upon the tree species set of the potential natural forest community in order to ensure the highest stability of the forest stands. Currently the dominance of Norway spruce would be replaced by European beech, if the forests in the montane vegetation belt in the Calcareous Alps of Austria would be constituted according to the natural vegetation (Koeck and Hochbichler, 2011).

Mixed forest stands with a high diversity of tree species according to the natural vegetation would show a lower degree of vulnerability towards various natural disturbances and also would be more resilient under climate change conditions. The adaptability of the set of natural tree species in the Calcareous Alps of Austria would also be given under climate change scenario conditions, despite the fact that some of the species would shift their potential spatial extension (Koeck and Hochbichler, 2011; Zimmermann et al., 2013). This is also related to the situation that the mean annual temperatures and the annual precipitation in this area can be regarded as benefitting for forest growth.

4.3.2. The karst system

From a hydrogeological point of view three zones can be differentiated within a karst system: the vadose zone, the semiphreatic zone and the phreatic zone. The phreatic zone represents the saturated part of a karst aquifer, where all more or less communicating voids are completely filled with water. The semiphreatic or intermediate zone is situated between the saturated and unsaturated zone. Its lateral and vertical dimension is variable in space and time. Depending on the hydrological situation this part of the karst rock belongs to the unsaturated or saturated zone. The vadose zone can be defined as the unsaturated zone of a karst aquifer in which gravity flow is dominant and in which voids may be wholly or partly filled with air or water (European-Commission, 1995b). The vadose zone includes also an existing open capillary fringe just above the saturated zone in which water is held by capillary action. It can be subdivided into topsoil (if present), epikarst (if present), karst and seepage. In the unsaturated zone water is predominantly moving in voids not completely filled with water until reaching the saturated zone. Mainly vertical flow directions are to be expected in the alpine area with its differences of level in landscape relief. Sections with gravitative flow can change to squeezing flux within small horizontal distances. It is to observe, that alpine karst is mainly characterized by distinguished karst water bodies within one mountainous area. This is mainly caused by morphogenetic processes, particularly provoked by changing of drainage relation during morphgenes. Also lithological differences like capability of karstification or geological features are responsible for complex karst aquifers. Karst springs situated higher as the resant drainage base indicate a disproportion between erosion of the drainage base and karstification. They are also fed by a saturated zone, even though they are not perennial.

Soils of karst systems in the Northern Calcareous Alps

Water infiltration into the (epi)-karst zone highly depends on properties of an overlaying soil cover. Thickness, rock content, soil texture and humus content together with biological activity determine the hydraulic conductivity and water storage capacity of these soils. Vegetation management indirectly influences biological activity and thus humus dynamics.

A high proportion of the Calcareous Alps is formed of carbonatic rocks, though clastic sedimentary rocks like, sand-, silt-, claystones and marl, biogenic radiolarite, quarternary deposits and, particularly in the eastern parts paleosols are widespread parent materials for holocene soil formation (Geologische-Bundesanstalt-Wien). Parent material and slope position are the main factors determining the amount of clayey weathering residues and thus soil development.

From weathering of pure limestones and dolomites only low amounts of clay are released. In such cases 'soils' are comprised solely of organic surface layers, which, in places, can reach a thickness of up to 1 m (see literature review in (Prietzel et al., 2013)). In the WRB soil classification (IUSS, 2006) these soils qualify as Lithic Leptosols or, if the organic layers reach a thickness of >10 cm, Folic Histosols. The latter humus forms are also known as 'Tangel' (for a detailed description of Tangel see supplementary material in (Zanella et al., 2011)). (Prietzel et al., 2013) could confirm the general hypothesis for the development of Tangel mainly from coniferous litter and dated the age of organic matter > 500 to 1400 years what is less than other publications describe (up to 8000 years). Soil depth and clay content increase usually along a catena from Rendzic Leptosols, Mollic (Leptic) Cambisols to Chromic Cambisols. Depending on clay content of the substrate, microclimate, vegetation and soil aeration, different humus forms may be found. In particular in shallow soils organic layers are important media for water storage and nutrient supply.

Chromic Cambisols are dominating flat residual terrain. At accumulating sites they show a tendency to waterlogging and gradually transit into Stagnosols. Mosaics of different soil and humus types vary frequently on a fine scale.

Eighteen percent of the soils in the eco-region ‚Northern fringe of the Austrian Eastern Alps' (Kilian et al., 1994), which mainly covers the Northern Calcareous Alps and the Flysch zone, exhibit a soil depth of less than 30 cm and soil layers with particularly high humus contents ((Englisch, 2011), Figure 2). Eighty percent of these shallow soils feature organic soil layers of Moder or Tangel-humus type. Even colluvial soils with Mull humus dynamics have high humus contents in the A-horizon.

Development of shallow soils with high humus content depends on constant input of vegetation residues. Undisturbed ecosystems with Folic Histosols and Lithic Leptosols have closed nutrient cycles. The vegetation cover may contain higher nutrient pools than the soil (Katzensteiner, 2003).

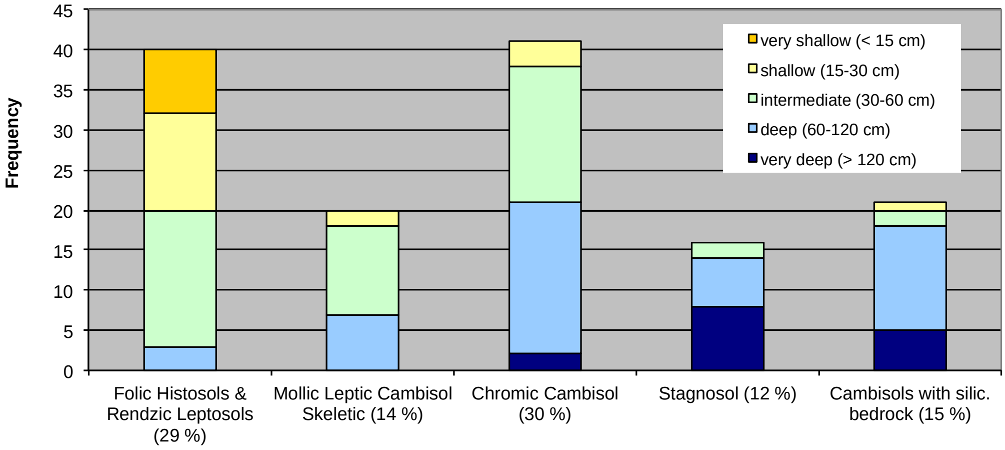


Figure 2: Forest soils in the ecoregion 'Northern Fringe of the Austrian Alps'. Source: Austrian Forest Soil Inventory, 140 profiles; data base query (Englisch, 2011). Soil types have been aggregated to groups. Rare soil types have been excluded from the statistics.

In general, shallow, humus rich soils are highly vulnerable to changes in land use. Transformation from natural forests to grazing land is known to promote erosion, in extreme situations a complete loss of soil cover has been observed also in parts of the Calcareous Alps (e.g.(Bauer, 1953); Figure 3). (Dirnböck et al., 2008) showed that the regeneration of the humus layer after pasture abandonment may only be around 10 cm during the first hundred years.

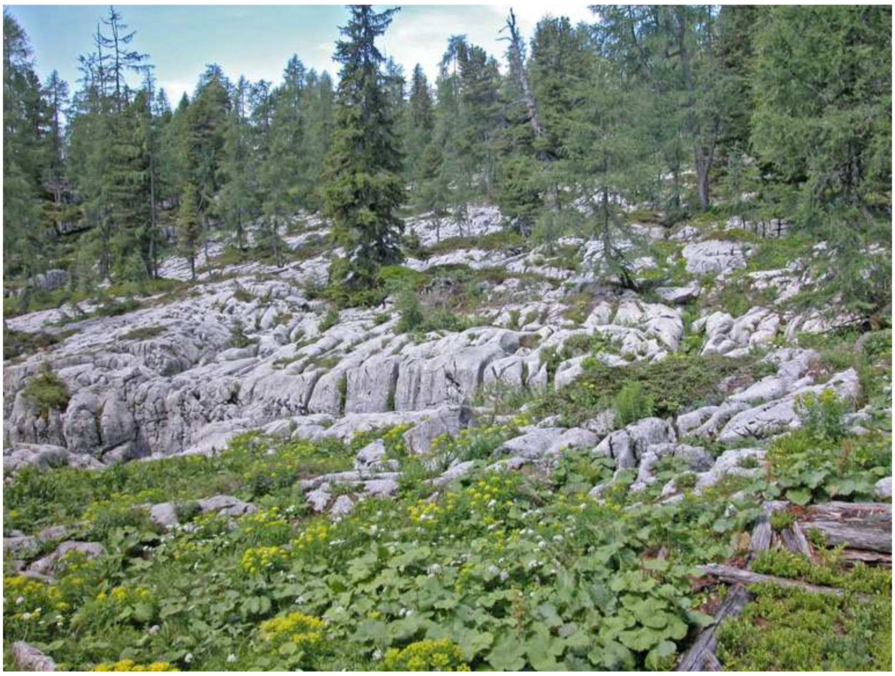


Figure 3: Indicators of pastoralism and soil erosion in historic times in a subalpine mixed *Larix decidua-Pinus cembra-Picea abies-* forest in Upper Austria. Round karren indicate weathering under a soil cover which was probably lost due to grazing; remnants of a stable and vegetation indicating nutrient accumulation in the foreground (©Katzensteiner).

Also forest operations may cause severe nutrient and humus losses from Folic Histosols and Lithic and Rendzic Leptosols, which may lead to a partial loss of soil functions (Bochter et al., 1981;

Katzensteiner, 2003). Even when operations are conducted with caution, humus losses may be substantial (Christophel et al., 2013). Particularly during phases of missing tree vegetation due to delayed regeneration after disturbance, dramatic humus degradation may occur. In chronosequences of successional stages after disturbance of montane forests on south exposed slopes in three regions of the Northern Calcareous Alps, (Katzensteiner et al., 2009) describe a decrease of average organic layer thickness from > 10 cm in mature stands to < 4 cm on sites without sufficient tree regeneration for more than 10 years. The regeneration fails due to a missing seedling bank in the mature stands, seed limitation, ungulate browsing and deteriorating site conditions. Similarly, (Prietzel and Ammer, 2008) found significantly thicker humus layers of fenced exclosures with sufficient regeneration compared to the situation outside where snow gliding caused severe erosion. (Hollaus et al., 2013) followed humus dynamics in a mature stand and windthrow areas of different age on a S-exposed slope over two years and could confirm the increase of rock cover and the decline of humus thickness after disturbance. (Mayer and Katzensteiner, 2012) attribute part of these SOC losses to increased autotrophic respiration. However, part of the losses are due to the breakdown of the tree root structures, followed by exposing subcutaneous voids so that particulate and dissolved organic matter is washed into the epikarst zone (Figure 4).

Figure 4: As tree root structures break down after disturbance, soil organic matter is partly washed into subcutaneous voids; the white color indicates recently exposed rock (©Katzensteiner)

Direct effects of changing climate (rising temperature, altered precipitation regime and snow cover) on soils are still uncertain (APCC, 2013). Increased mineralization rates of organic matter due to higher temperatures (Schindlbacher et al., 2009; Schindlbacher et al., 2012) may be compensated by inputs from increased net primary productivity. (Schindlbacher et al., 2012) also showed that extended drought periods inhibit soil organic matter (SOM) decomposition on limestone soils. A shorter duration and lower thickness of snow cover may also affect microbial activity (Groffman et al., 2001): 'Colder Soils in a Warmer World') and SOC stocks of soils of the Calcareous Alps (Djukic, 2011).

Indirect effects of climate change on forest ecosystems, such as wildfire, windthrow and insect outbreaks, may be more severe than direct effects because SOM and related pollutant losses are severe after disturbance. (Seidl et al., 2011) show that climate change was as important as forest management a driver of the increase in forest area burnt, wind and bark beetle damage in Europe. Forest fires can have severe direct effects, as organic soil layers may be completely burnt. The recovery of vegetation and soils in the Limestone Alps may take decades to centuries, in particular when post fire erosion processes like avalanches accelerate erosion and inhibit regeneration (Sass et al., 2012).

Figure 5: Soil loss and vegetation succession in the subalpine belt of the Calcareous Alps 10 years (left) and 63 years (right) after fire disturbance (©Katzensteiner).

Cambisols and Stagnosols may be considered less sensitive to disturbance. Nutrients like phosphorus and potassium are retained efficiently in mineral soil horizons, recovery with herbaceous vegetation and grasses prevents erosion and keeps rare nutrients in the cycle. Compaction by forest grazing or by heavy machinery may however destroy soil structure and thereby have negative impacts on the infiltration process.

The epikarst zone

'The variable characteristics of the epikarst strongly influence its capacity to absorb, store and transmit precipitation. Where the karst surface is largely bare, the uptake of water is determined by the characteristics of the rock, but where its covered it is controlled by the nature of the soil' (Williams, 2008).

In the alpine life zone, in erosive slope positions, the (epi)-karst (if present) is frequently exposed at the surface. But also at forested sites, frequently a patchy pattern of bare rock and soil cover can be found. Soil CO2 itself may drain down into any underlying fissures or caves because it is a heavy gas (Figure 6). In the Northern Hemisphere maxima of underground CO2-content occur in July – September, when CO2 concentration may be two to four times as great as in winter. Whether the surface is bare or covered by soil, the finer particulate and dissolved organic carbon produced by decay filters down in the vadose percolation zone (Epikarst). In the vadose (aerobic) percolation zone this material produces CO2 by bacterially mediated oxidation. Cave streams, especially floodwaters, will pick up this excess CO2 and so boost their solvent capacity (Ford and Williams, 2007).

(Katzensteiner, 2000) followed the fluxes of precipitation, passing the canopy, seepage from a Folic Histosol/Lithic Leptosol and runoff from exposed bare rock down to a sinkhole 10 m belowground

(Figure 7) over the vegetation period. The results clearly show the transformation of organic carbon and nitrogen in the epikarst zone, probably due to microbial processes in biofilms, as well as the change of the alkalinity of the seepage. The vegetation/soil system is still a sink for nitrogen. In humus percolates nitrogen is found mainly in organic form. When infiltrating the epikarst zone, organic carbon and nitrogen are mineralized.

The vadose zone has in areas off the conduits a filtering and retardation capacity in the fine fractured rocks. This was demonstrated e.g. for PAHs and BCHs (Simmleit and R., 1986) and for bacteriophages (Bricelj and Čenčur-Curk, 2005).

In many alpine karst areas the exact thickness of the vadose zone is often unknown due to the lack of drill holes and larger cave system, but can be estimated to be several hundred of meters thick. In active alpine zones rapid rate of uplift, denudation and valley incision can give rise to rapid unloading. As a consequence, all the fissures are relative open near the surface where the pressure is least, but close with depth (Ford and Williams, 2007). The assessment of geological structures withing structural-geologic models helps to classify to water conductivity of lineamants considering also recent tectonical movements.

Besides its effects on water quality and runoff, epikarst structures, fissures and small pores in carbonate rocks and hanging aquifers can provide the water supply for the vegetation even over longer dry periods.

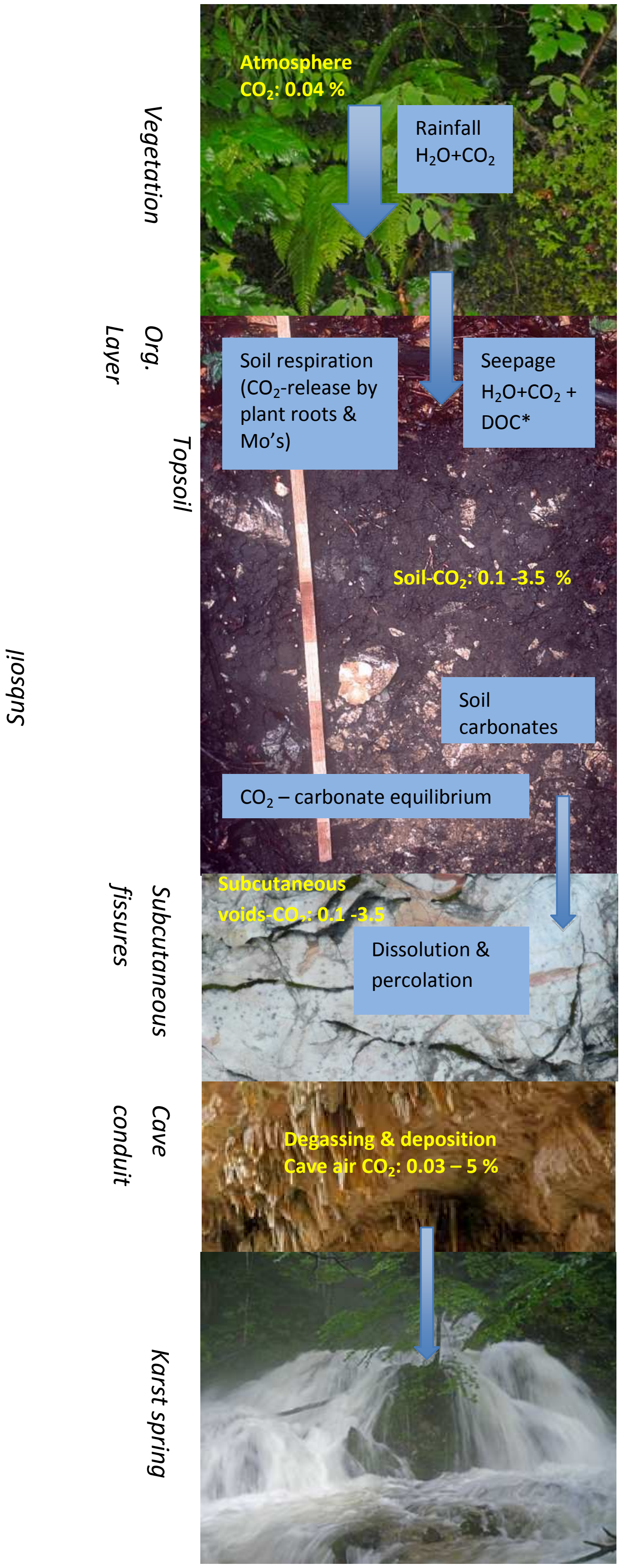
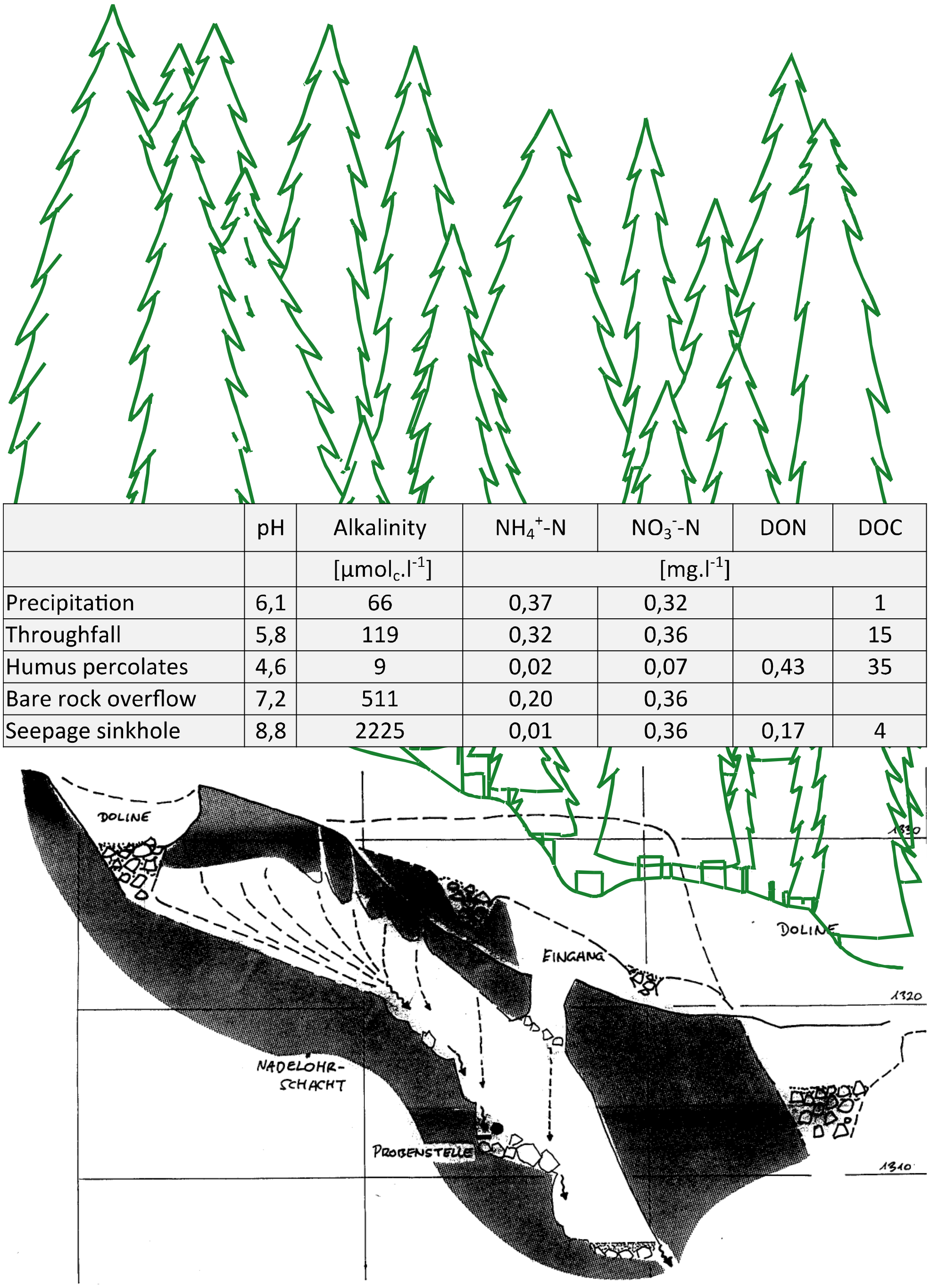


Figure 6: Epikarst – the karst engine house (modified after Gillieson, 1996)

MOs…Microorganisms,
DOC…Dissolved organic carbon



	pH	Alkalinity	NH_4^+-N	NO_3^--N	DON	DOC
		[μmol$_c$.l^{-1}]	[mg.l^{-1}]			
Precipitation	6,1	66	0,37	0,32		1
Throughfall	5,8	119	0,32	0,36		15
Humus percolates	4,6	9	0,02	0,07	0,43	35
Bare rock overflow	7,2	511	0,20	0,36		
Seepage sinkhole	8,8	2225	0,01	0,36	0,17	4

Figure 7: Changes in water quality passing a karst system (3 vegetation periods, concentrations weighted by water flux; data source: (Katzensteiner, 2000))

Karst water

About 50 % of the drinking water used in Austria comes from porous groundwater resources, 50 % mainly from karst springs. Therefore karst and fractured groundwater resources contribute significantly to the drinking water supply. Since these resources have a high potential regarding further exploitation, karst areas in the alpine regions of Austria play an important role due to their high amount of precipitation (1000 – 3000 mm.a-1). Major cities like Vienna rely on karst water and provision of pristine water is an important forest function in water protection zones of karst areas (Figure 8).

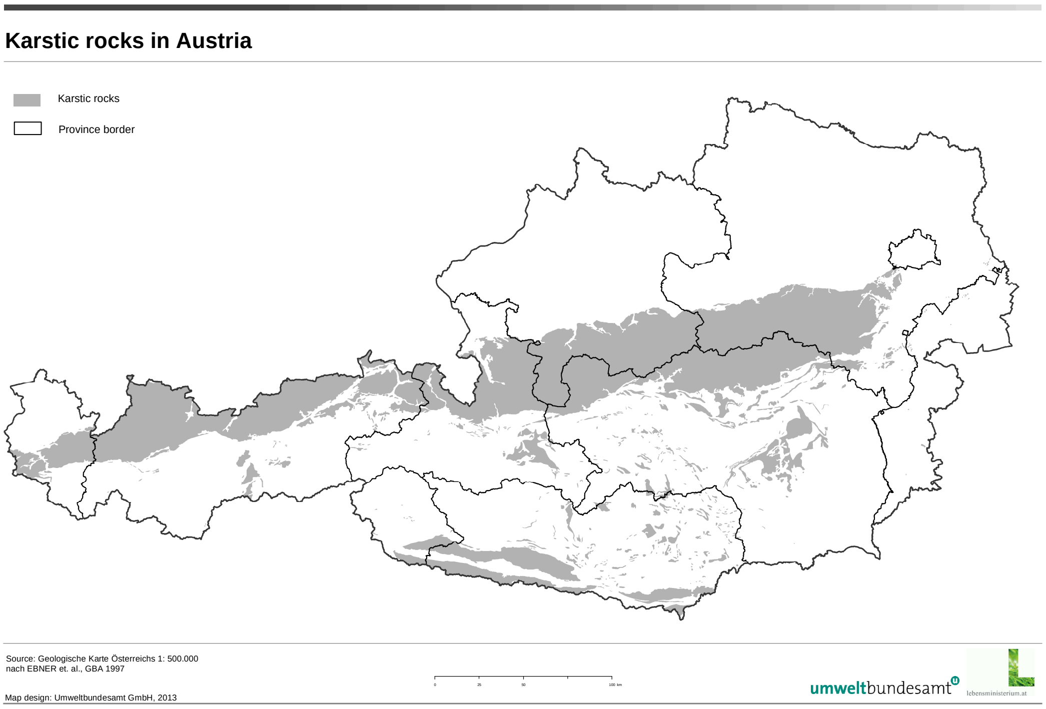


Figure 8: Carbonate outcrops and water protection zones in Austria (Kralik *et al.*, 2006)

Local pollutant impacts, long-term effects of transboundary air pollution (originating mainly from industry, traffic, domestic fires and agriculture), climate change and radioactive fallout are potential impacts or risk on karst water. Due to the mostly insufficient upper confining bed in karst catchment areas, karst water is particularly vulnerable to pollution. Moreover rainwater seeping into karst-cavities is usually not filtrated sufficiently, so that monitoring of springs in recharge areas is one way to protect the quality of karst water (European-Commission, 1995a).

Protection and monitoring of water bodies have a long tradition in Austria. Since 1991 the quality of Austrian groundwater, rivers and lakes has been monitored according to uniform, legally established criteria of the Water Act and its detailed ordinances. This monitoring programme comprises both groundwater and surface waters. It is one of the major cornerstones of the precautionary environmental protection practised in Austria.

Alpine karst waters are relatively cool (80 % of the values 5-10 °C) due to their high elevation recharge area and short mean residence times. The proportion of dissolved substances is quite low, represented by low electrical conductivity values (180-520 µS.cm-1) and low total hardness (5-15 °dH). Electrical conductivity and total hardness are even declining with altitude, probably as a result of the combination of dilution due to higher precipitation rates and less solution due to the absence of root-CO2 above forest line and shallow soil depth (Kralik et al., 2006).

The concentrations of calcium and magnesium in karst water depend on the deposits of limestone and dolomite in the recharge area. Higher sulphate and chloride values are correlated to gypsum and saline deposits. 95 % of all carbonate (karst) water monitoring sites in Austria belong to the Ca-Mg-HCO3-type, only 5 % to the SO4-type. Within the Ca-Mg-HCO3-type 20 % are related to the Ca-subtype (where the ratio of Ca to Mg is higher than 6) (Kralik et al., 2005).

More than 90 % of the springs of the water quality network of Austria featuring natural composition below any limit values. Only 8 % temporary exceed limit values due to natural, geologic sources such as sulphate and chloride leaching of gypsum and evaporites, but also anthropogenic emissions like phosphate and atrazine.

Significantly higher heavy metal concentrations can predominantly be traced back to mainly natural mineralisation.

Microbiological parameters are the main reason for contamination found in Alpine karst springs. Especially during rain events or snow melting, which is normally connected to an increase of discharge, abrupt increase of microbial contamination in karst water resources can be observed. The abrupt increase and slow decrease is comparable to the curves of dye tracer experiments and spectral absorption coefficient at 254 nm (SAC254) (Dosch, 1956; Pavuza and Traindl, 1985; Zibuschka et al., 2004; Farnleitner et al., 2010; Stadler et al., 2010).

About 30 % of Austria’s total groundwater abstraction (also including industry and agriculture) is coming from karst and fractured rock. More than 50 % of the demand of drinking water supply is covered from the alpine area. The actual and predicted future water demand needed by the alpine area of Austria is about 2 % of the mean groundwater recharge of this area. This means that the percentage of exploitation is quite small and normally not in conflict with a good surface water and groundwater ecology. In normal years more than four billion m3.a-1 (130.000 l.s-1) coming from alpine bedrock resources are available for other types of uses. This is about six times higher than the current amount used for drinking water supply in Austria assuming constant amount of abstraction in future (Harum et al., 2001).

4.4 Forest management and disturbance effects upon water quality and quantity

Numerous publications and review papers treat the effects of forest cover and forest management on water budget and water quality and there is little contradiction between findings of different experiments. Therefore basically a synthesis of general findings is provided based upon (Raulund-Rasmussen et al., 2011), (Rothe et al., 2002; Rothe, 2005), (Augusto et al., 2002), (Gundersen et al., 2006), (Bredemeier, 2011) and (Butterbach-Bahl et al., 2011) and individual experimental results are only presented if specifically relevant for karst.

At present, nitrogen pollution seems to be the most widespread threat for groundwater in the Northern hemisphere. An excess input of atmospheric nitrogen, but also natural disturbances may lead to a disruption of the N-cycle in forests and lead to increased output rates. Therefore the review about forest management effects on water quality mainly focuses on nitrogen.

But nitrate is not the only relevant pollutant. Especially in karst areas the dynamics of increased turbidity values or bacteria concentrations in spring water play an important role in terms of water quality and are mainly caused by strong precipitation events or fast snow ablation processes (Celico, 2011; Koeck and Hochbichler, 2011). Both turbidity and bacteria concentrations in the karst water can be influenced by land use management. In addition is to mention, that detailed investigations of karst water resources of the Northern Calcareous Alps at event-scale showed, that the Sepctral Absorption Coefficient is a clearly surface related indicator whereas turbidity is also caused by karst sediments (Stadler, 2010). Hence forest management can also contribute to either increased water quality problems in the case of clear-cut managed forest ecosystems or on the other hand to integral drinking source water protection. The latter case can be achieved with the application of target-oriented forest management like e.g. continuous cover forestry or the focus on stability and resiliency of the forest ecosystems (Koeck and Hochbichler, 2012).

4.4.1 Forests compared to other land uses

Forests compared to other land uses are characterized by higher water consumption. They may decrease peak runoffs, but at the same time will provide a higher continuous base flow (numerous references in (Raulund-Rasmussen et al., 2011; Schleppi, 2011). In particular the mediating effect of the forest cover on runoff is of specific importance in the Calcareous Alps with high precipitation rates and usually a thick winter snow cover.

The most important effects of forests within the context of drinking source water protection in humid areas like Austria can be related to the provision of good infiltration conditions for precipitation or snow melt water, the storage capacity for water which especially is given within the forest soils and in the prevention or mitigation of erosion processes. These three main effects contribute to the protection of drinking water sources and if the drinking water protection functionality of the forest ecosystems (WPF) is given on an optimal level, the use of the sources for water supply becomes possible. Hence the optimization of the WPF becomes the central target of silviculture and forest management within drinking water protected (Koeck and Hochbichler, 2012).

Most forests have evolved as nitrogen limited ecosystems characterized by low input rates compared to other land uses. In these situations a tight retention of inorganic nitrogen is characteristic, output occurs almost entirely in organic form (overview in (Gundersen et al., 2006)). At small input rates, low output rates can be expected (review in (Galloway et al., 2004)). Increased chronic nitrogen input to forests has however dramatically altered nitrogen cycles and has caused nitrogen saturation, with output rates equal or higher than input rates (Aber et al., 1989). (Gundersen et al., 2006) evaluated input-output relations from 78 undisturbed, mature temperate forest ecosystems in Europe. Above a threshold of approximately 10 kg.ha-1.a-1 N in throughfall, many sites show elevated nitrate leaching, above N-input rates of 25 – 30 kg.ha.a-1 all sites showed elevated leaching rates. (Kiese et al., 2011) showed that in Germany nitrate leaching rates reach up to 80 kg NO3-N ha-1.a-1 and 15 % of the Bavarian forest ecosystems showed mean seepage water nitrate concentrations exceeding the former German threshold for drinking water of 25 mg NO3 l-1 and 8 % of all forest ecosystems exceeding the EU threshold of 50 mg NO3 l-1. In the Calcareous Alps input rates differ significantly between the few long-term measurement sites and show a pronounced fluctuation. In the Austrian ICP Level II monitoring Network, (Fürst et al., 2012) found deposition rates between 3 and 10 kg.ha-1.a-1 in Tyrol and between 15 and 30 kg.ha-1.a-1 of inorganic N in Upper Austria. Exceedance of input thresholds (Critical Loads) can be found in the Northern Alps and the eastern part of Austria whereas nitrogen saturation does not seem to be a common phenomenon in Austria (Jandl et al., 2012).

4.4.2 Choice of tree species

The most important aspects related to the choice of tree species in forested drinking water protected areas (DWPA) are stability and resiliency of the created forest stands. This primary requirement calls for tree species distributions close to the potential natural forest community, as this provides the highest degree of stability (Tüxen, 1956). Only stable forest stands can prevent erosion processes and hence protect water quality and also the temporal distribution of spring discharge. Hence the homogeneous Norway spruce (Picea abies) plantations established at various different Austrian forest sites cannot be regarded as appropriate forest cover in DPWA and adaptive forest management towards site conditions comes into the focus of attention. Instead of homogeneous conifer plantations the natural tree species diversity according to the site conditions becomes the aim of forest management (Koeck and Hochbichler, 2011). This thematic field will be explained in chapter 4.5 “Concepts for vulnerability mapping” in detail.

Tree species distributions also influence net precipitation rates and water quality parameters. The choice of tree species has a moderate impact upon water consumption but alters the pattern of snow distribution and interception. While evergreen forests have rather high interception throughout the year, deciduous forests have low interception in the dormant season (Raulund-Rasmussen et al., 2011; Schleppi, 2011). The interception rate depends on precipitation amounts, intensity and duration of single events and their distribution over the year as well as on vegetation structure and properties. The species effect upon the water balance may be mediated by high transpiration rates of broadleaved forests in the vegetation period compared to coniferous forest (see (Raulund-Rasmussen et al., 2011). There may be pronounced plant-soil feedback mechanisms. Deeper rooting and higher activity of soil macro-fauna can improve soil structure under beech, thus leading to improved infiltration and decreased surface runoff.

Hydrological investigations by (Köck, 2008) in the Northern Calcareous Alps of Austria confirm the higher intercepted rain evaporation in pure spruce stands compared to mixed spruce/beech/fir stands. There was a clear relation to duration and intensity of precipitation events. Therefore single years differed considerably (mixed stand 20 to 40 % interception loss in the vegetation period compared to pure spruce stand 27 to 47 %). A pronounced effect of species composition and stand structure was also observed for snow distribution. Compared to a closed spruce stand, snow heights were 32 to 116 % higher in a mixed stand and 57 to 183 % higher in a regeneration plot.

In high elevation parts of Koeck’s investigation area, dwarf pine (Pinus mugo) stands have been compared to a subalpine pasture. A pronounced lateral transport of snow from pastureland to dwarf pine stands could be observed in early winter, also preventing soil frost in the pine stands. In high winter snow cover was thicker at pastureland, accumulating 930 mm water equivalent. In spring, snowmelt started earlier under dwarf pine. A subalpine spruce fir forest with tree clusters and small gaps in between, typical for high elevation forests, showed pronounced snow accumulation in gaps and delayed snowmelt rates in spring. With respect to karst hydrology these differences in snow distribution and snowmelt patterns are of particular importance for the runoff process.

With respect to water quality, (Rothe, 2005) concludes 'Tree species likely influence N leaching in areas with high N deposition. Nitrate concentrations in conifer forests are typically higher than for broadleaved forests'.

This general pattern seems to hold true also for the Calcareous Alps. High seepage rates may however 'hide' nitrogen saturation situations.

At an Integrated Monitoring site in the Calcareous Alps in Upper Austria, (Jost et al., 2011) could see clear differences in total nitrogen input between a spruce dominated stand (27 kg.ha-1.a-1 in throughfall) and a beech dominated stand (21.1 kg.ha-1.a-1 in throughfall), while bulk deposition was 18.7 kg.ha-1.a-1 (7.1 kg.ha-1.a-1 NO3-N, 8.1 kg.ha-1.a-1 NH4-N, 3.4 kg.ha-1.a-1 Norg). The result shows again the already well-known difference between coniferous and broadleaved systems. An important message is, that organically bound N significantly contributes to total N deposition, a fact frequently neglected in monitoring networks. While seepage N-output of the spruce stand (stocking at deep Cambisol) is already in the same range as input, the mixed stand (stocking at shallow Leptosol) seems to be still a sink for nitrogen. Output is mainly driven by pulse events like snow melt. During such events, nitrate concentrations in the seepage can reach 10-15 mg NO3-N l-1. However, in general, nitrate concentrations are still low (in average below 2 mg.l-1) due to dilution effects.

In close proximity to the sites mentioned above, (Katzensteiner, 2000) compared spruce and beech stands on different soil substrates. Inorganic nitrogen fluxes below canopy of beech at a rich Mollic (Leptic) Cambisol over the vegetation period were in the same range as bulk deposition, partly even a net retention of reduced nitrogen in the canopy was observed. The nearby spruce stand characterized by Cambisol showed a clear net enrichment of inorganic N below canopy. The output rates showed a pronounced year to year variation. They were higher under beech than under spruce, indicating nitrogen saturation. A spruce stand at a N-deficient site (see Figure 6) lost almost no inorganic N from the rooting zone and showed a net retention of N. There was however a substantial outflux of organic N from the system, which was mineralized later in the epikarst zone. In all stands average nitrate concentrations in seepage and in the epikarst were below 10 mg.l-1.

For the drinking water protected area (DWPA) of the city of Vienna located in the Eastern part of the Northern Calcareous Alps, (Köck, 2008) found low nitrate concentrations in seepage water from different land use types, like subalpine pasture, Krummholz of Pinus mugo, mixed European beech (Fagus sylvatica)/Norway spruce (Picea abies)/Silver fir (Abies alba) forests and pure Norway spruce stands. The general pattern showed increased nitrate concentrations in throughfall and soil solution under Norway spruce (rarely exceeding 10 mg l-1) compared to mixed stands with European beech and low concentrations in the soil solution of a regenerating mixed stand. Under Pinus mugo the nitrate concentrations in seepage frequently were below detection limit. In the karstic alpine DWPA of the cities Vienna and Waidhofen/Ybbs nitrate actually does not form a threat to water quality (Koeck and Hochbichler, 2011).

(Jandl et al., 2008) calculated climate change and deposition scenarios, based on monitoring data from a forest stand with calcareous bedrock in Tyrol. The modelling results suggest that in the case of a 2.5 °C temperature increase, even under a deposition reduction scenario, nitrate output rates with seepage will increase due to increased nitrification rates.

From a safeguarding perspective a considerable share of broadleaved and/or deep rooting tree species in the mixed coniferous/deciduous belt is recommended despite the dilution effect due to high precipitation rates.

4.4.3. Stand and forest management

On a stand and a small watershed scale, harvesting regime will have the highest impact on water consumption and runoff patterns. Clear cutting more than 20 % of a watershed will increase runoff rates in a proportional relation to precipitation amount and area cleared. Depending on site conditions and regrowth rates, the impact may last from few years if forest regenerates quickly, to decades if the site is heavily disturbed. In addition the construction of roads, skid trails and landings, as well as soil compaction from harvesting operations may increase peak runoff (Raulund-Rasmussen et al., 2011).

A disruption of the nutrient cycle by thinning or clearcut has pronounced effects on the nitrogen cycle. Additional slash input to the soil and altered mineralization rates lead to higher availability of inorganic nitrogen. As plant uptake is partly disrupted, pronounced leaching losses may occur. ‘In general, the nitrate concentrations in soil and stream waters increase with peak nitrate concentrations within 2-3years after clearcut’ (Gundersen et al., 2006). A similar pattern was observed by (Katzensteiner, 2003) at a chronosequence of different development stages of Spruce on a site with Folic Histosol to Chromic Cambisol. In his study nitrate concentrations peaked already during snowmelt one winter after harvesting (> 30 mg.l-1), but returned to pre-harvest levels close to detection limit already after three years. Organic nitrogen concentrations in seepage remained however high and were probably nitrified in the epikarst.

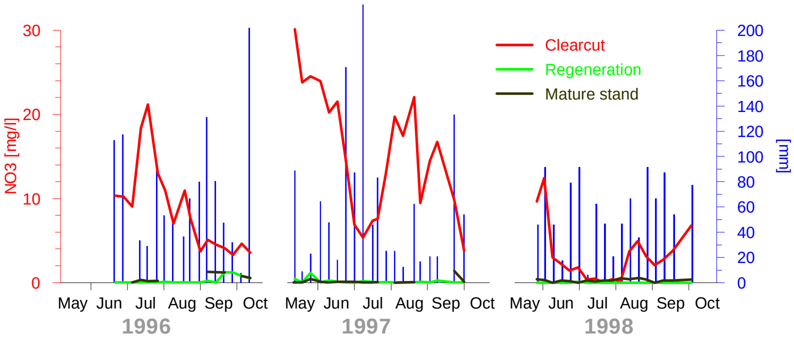


Figure 9: Nitrate concentrations in the seepage below the rooting zone of different successional stages of a Norway spruce ecosystem (Katzensteiner, 2003)

While at a stand scale the effects of harvesting on amount and quality of seepage may look dramatic, at the scale of larger watersheds may be leveled out. In a modeling study comparing different forest management regimes, (Duncker et al., 2012) come to a similar conclusion.

Forest management concepts like shelterwood cut, selective harvesting or continuous cover forestry promoting gap regeneration may be an option to prevent clear-cut phases and its negative consequences.

(Weis et al., 2006) compared a shelterwood cut to a clear-cut. The net nitrogen losses were similar in both systems, while in the clear-cut 85 % of the losses occurred within 3 years, in the shelterwood cut system the effects were more evenly distributed over a 20-year period. Concerning gap regeneration there are reports on severely elevated nitrate concentrations in the gaps, and they seem to be independent from gap size (e.g. (Bauhus and Bartsch, 1995), (Ritter, 2005)).

The advantages of small scale silvicultural measures within the concept frame of continuous cover forestry (Thomasius, 1996), like e.g. small gap cutting or shelterwood selection system are given due to their small area of timber cutting in relation to the clear-cut system. Hence the related effects like mineralization and decomposition processes occur only on small spatial extensions, what supports the possibility that the mobilized nutrients are either absorbed by neighbouring trees or diluted in the karst aquifer.

4.4.4 Road construction

Road construction in mountainous terrain may lead to erosion and increased sediment input into the karst system. In some cases like on sites with shists, marls and claystones the probability of landslides is increased with the construction of forest roads. Additionally it has to be considered that 4-5 ha of hydrological optimized forests are necessary to compensate surface runoff increase and storage loss of 1 ha forest area used for road construction (Markart et al., 2011). Also the effect of concentrating runoff and stopping lateral flow which often occurs in the case of dolomitic bedrocks has to be taken into account. The retention of buffer strips along streams and karst springs may not only reduce sediment input, but also can remove nitrate by denitrification (references in (Raulund-Rasmussen et al., 2011).

4.4.5 Site preparation

Site preparation plays a minor role in contemporary Central European mountain forestry. The application of pesticides in Close-to-Nature Forestry or Combined Objective forestry as defined by (Duncker et al., 2012) is usually restricted to control major outbreaks of spruce bark beetle by treating residues or to prevent pine weevil damages in afforestations. Though the common agents like pyrethroides are normally strongly absorbed at soil particles, there is a certain risk of water contamination when applied in karst areas. Pyrethroides are highly toxic to aquatic organisms (http://www.epa.gov/oppsrrd1/reevaluation/pyrethroids-pyrethrins.html as accessed June 03, 2013), also when transported with particles. The application is critical in situations where epikarst is exposed close to the surface.

4.4.6 Natural disturbances windthrow, bark beetle, insect defoliation

Windthrow and biotic disturbances may impact runoff, erosion and nitrate leaching. (Huber et al., 2004; Huber, 2005) showed long lasting nitrate leaching after bark beetle attacks in the Bavarian Forest National Park. The fact that natural disturbances play an important role within mountainous catchment areas was also shown by (Koeck and Hochbichler, 2011).

(Kohlpaintner and Goettlein, 2011) compared the chemical composition of seepage after a windthrow of a Norway spruce forest at a 'Dachsteinkalk'-karst plateau close to Berchtesgaden to an intact mature stand. They found pronounced differences of seepage water composition along the soil mosaic and between intact stands and windthrow sites. Within the intact stands, the DOC concentrations under mineral soils were below 20 mg.l-1 while under Folic Histosols they were partly above 50 mg.l-1. The nitrate concentrations under soils of intact stands were close to detection limit. After disturbance, DOC concentrations under mineral soils raised only slightly, whereas the concentrations increased considerably under shallow organic layers overlaying bedrock material (up to 90 mg.l-1). The nitrate concentrations in seepage were dependent on the thickness of the organic layer, reaching a peak of 100 mg.l-1 under thick organic layers (Tangel) one year after the windthrow event. At the same time potassium, a limiting nutrient was leached to a considerable extent from organic soils. Under mineral soil the nitrate concentrations remained below 10 mg.l-1.

Weis et al. (personal communication) found a rapid increase of nitrate concentrations (> 50 mg.l-1) in seepage of a Norway spruce stand after a bark beetle attack in the Limestone Alps. Due to the currently severe bark beetle damage in large parts of the Calcareous Alps, detrimental effects on karst water may be a likely effect.

4.5 Concepts for vulnerability mapping

Groundwater vulnerability mapping is a common tool for water management purposes. COST action 620 (Zwahlen, 2003) distinguishes intrinsic vulnerability of groundwater to contaminants, taking into account geological, hydrological and hydrogeological characteristics of an area, independent of the nature of contaminants and the contamination scenario and specific vulnerability, which takes into account properties of particular contaminants. For intrinsic vulnerability, the determination of overlying layers (soil and lithology), concentration of flow (swallow holes) and intensity and quantity of precipitation are considered (Zwahlen, 2003; Goldscheider, 2005). (Kralik, 2001) compares different concepts; the vegetation cover is rarely treated in detail. (Kobler, 2004) presents a vulnerability and risk zonation for karst spring water, where, in addition to parameters described above, vegetation cover and it's filtering and buffering capacity for diffuse contamination is classified. Still his approach does not account for dynamic properties of ecosystems.

The delineation of homogeneous hydrological response units as a basis for land management is a different approach (Engel, 1996; Gurtz et al., 1999). The 'Forest Hydrotope Model' developed by (Koeck et al., 2007) and (Koeck and Hochbichler, 2011) has been applied successfully to develop management plans for two drinking water protected areas (DWPA) of the Calcareous Alps (see chapter 4.6 "Adaptive forest management"). The Forest Hydrotope Model can also be applied in order to estimate the intrinsic vulnerability given by e.g. soil types or actual forest vegetation. All of the concepts described above need soil information in different degrees of detail, information, which is lacking for most forest areas in Austria.

4.6 Adaptive forest management concepts

4.6.1 Adaptive forest management

In order to provide the protection of drinking water sources, forest management has to guarantee a low disturbance regime. This can be fulfilled by low scale disturbances given by forest management itself and by the creation of stable and resilient forest stands which hence are not that susceptible to natural disturbances. Within this context adaptive forest management and best practices for drinking water protection come into the focus of attention. The combination of both can be summarized under target-oriented silviculture for drinking water protection.

As first step, adaptive forest management towards site conditions has to be achieved. In the past century Norway spruce plantations were established in Austria on various different forest sites, thereby in many cases creating instable forest stands. The Forest Hydrotope Model (FoHyM - (Koeck et al., 2007; Koeck and Hochbichler, 2011)) provides detailed information about the site conditions within a DWPA. The integration of geology (bed rock types), soil type, plant sociological data and relief information was used for the definition of the forest hydrotope type, which was based on the potential natural forest community in the sense of (Tüxen, 1956). For each forest hydrotope type, the potential tree species diversity was defined, which also reflects the highest degree of stability for forest vegetation. The basis for FoHyM was the forest site mapping survey in the drinking water protection forests of the city of Vienna (Koeck et al., 1996; Gatterbauer, 1998; Weidinger and Mrkvicka, 2001) and the hydrotope mapping survey for the DWPA of the city of Waidhofen/Ybbs (Koeck et al., 2012; Koeck and Hochbichler, 2012). The actual vegetation cover and its properties were mapped and its deviation from a status fulfilling an optimal water protection functionality (WPF) was assessed and defined. Hence the improvement potential for forest management in terms of water protection was defined for each forest stand within the DWPA. FoHyM therefore is an effective tool for adaptive forest management towards site conditions.

But also the adaptation of forests to climate change conditions can be achieved by the application of FoHyM. It has to be highlighted that the tree species diversity given by the forest hydrotope definitions is an excellent starting point for any adaptation towards any climate change conditions, as diversity creates a higher degree of forest stand resiliency. The knowledge about the potential tree species diversity for each forest hydrotope enables the estimation of the tree species changes caused by climate change scenarios which was carried out in detail for each hydrotope type (Koeck and Hochbichler, 2012).

4.6.2 Best practices for water protection

In order to confirm with the requirements of an integral source water protection, best practices for forestry were defined (Koeck and Hochbichler, 2012), (Richards et al., 2012). The most important issue is the prohibition of the clear-cut system, as it causes various negative effects on water quality and successive erosion dynamics in steep terrain. This can be achieved by the application of continuous cover forest systems (CCF) as alternative (Thomasius, 1996). The CCF requires the creation of multi-layered and uneven-aged forest stands with the tree species composition according to the forest hydrotope definitions and continuous regeneration dynamics regarding the tree species specific light ecology. Only small scale silvicultural concepts and measures can be applied within this context, like e.g. single tree harvesting, the gap cutting system (small gaps up to one tree length in diameter) or the group-selection system (Mayer, 1974).

In the course of silvicultural measures the limitation of the forest stand volume reduction has to be defined between 15-25 % of the forest stand volume. Also the crown cover percentage should never be reduced below 70 % in the montane zone and 60 % in the subalpine zone. Both measures guarantee that the disturbance regime caused by silviculture is kept on a low level and that the stability of the remaining forest stands (e.g. in case of strong winds) is still given on a high level. Trees which show high stability and vitality parameters should be left on the site, what is a distinct difference to timber forests.

Of importance are also buffer strips around dolines, sink holes and brooks, which ensure that water quality is not diminished by surface flow or lateral flow into these landscape elements. The buffer strips should be kept with stable and undisturbed forest vegetation cover.

In order to keep a high level of stability and resiliency of forest ecosystems, the adequate amount of deadwood is of significance as it ensures the presence of several organisms which guarantee a stable forest ecosystem.

Also the genetic pool of the established trees in a region is of central importance, as they have already survived the changing climate during the last centuries or millennia and hence can be regarded as adapted to the specific site conditions in terms of climate change processes of the past. This will be of crucial importance for the stability of forest succession under any upcoming climate changes.

Adaptive forest management towards climate change has to be carried out following a periodical and stepwise strategic concept (Koeck and Hochbichler, 2012) and should first be applied after a detailed evaluation of the de facto climatic development (FCD) in comparison to the climate change scenarios. If the FCD conforms to the scenarios, silvicultural measures like planting of migrating tree species (species spreading into neighbouring life zones due to changing site conditions) can be carried out according to the elaborated management plans. If the FCD deviates from the scenarios, new adaptive forest management plans would have to be elaborated according to the given climate development.

The application of the whole catalogue of best practices within forested DWPA ensures the sustainable safeguarding of the water protection functionality of the forest ecosystems. Adaptive forest management towards site conditions and towards climate change is part of this catalogue.

4.7 Policy implications related to “Forest & Water”

4.7.1 EU-Legislation and other transnational resolutions

EU-Water Framework Directive, 2000

After a long discussion process the Water Framework Directive (WFD) has been established in the year 2000 to harmonise the legal and conceptual framework for water supply. Its main goals are the creation of a water management framework, protection and enhancement of the condition of aquatic ecosystems and the promotion of sustainable and equitable water use. The WFD includes a comprehensive water management plan which encompasses the whole river basin as well as several elements – like increased public participation in water management and the introduction of economic tools - which were not covered by European directives so far. Contrary to previous EU water protection laws this directive regards all water bodies and not only “usable” water resources. Environmental targets, however, remain to be the main object of the WFD: all EU Member States have to obtain or maintain a ‘good condition’ of their water resources within 15 years. However, there are several exceptions and derogations which considerably compromise the WFD’s legal effect and potential outcome (Hall et al., 2004).

In the WFD is stated that all the Member States have to consider the cost-covering principle and include environmental and resource-related costs in the costs of water services. Water pricing policy should provide incentives for efficient use of water resources and thus contribute to the environmental goals of the directive. In this way the WFD gives the opportunity to legal implementation of measures to protect and secure water supply in the respective Member State. Furthermore it could mean a break-through of the compensatory principle in future. Accordingly, services of water protection beyond ordinary forest soil use, would have to be remunerated in correspondence with transparent evaluation criteria (Rappold, 2007).

The EEA State of Water report and the Commission assessment of the Member States´ River Basin Management Plans (RBMPs) developed under the WFD concur that the objective “good condition” of the water resources is likely to be achieved in slightly over half of EU waters. Major additional action is therefore needed to preserve and improve EU waters. Therefore, the Commission proposes the “Blueprint to Safeguard Europe’s Water Resources”. Its long-term aim is to ensure the sustainability of all activities that impact on water, thereby securing the availability of good-quality water for sustainable and equitable water use. The key themes are: improving land use, addressing water pollution, increasing water efficiency and resilience, and improving governance by those involved in managing water resources. The Blueprint will help to achieve the goals by identifying obstacles and ways to overcome them. There is a need for better implementation and increased integration of water policy objectives into other policy areas, such as the Common Agriculture Policy, the Cohesion and Structural Funds and the policies on renewable energy, transport and integrated disaster management (European-Commission, 2012).

Ministerial Conference on the Protection of Forests in Europe (MCPFE)

The Ministerial Conference on the Protection of Forests in Europe (MCPFE, synonymous Helsinki Process and Forest Europe since November 2009) is a pan-European forest policy process at ministerial level, to develop guidelines, criteria and indicators for the protection and sustainable management of forests. Since 1990 every 3 to 5 years ministerial conferences and their follow-up processes were conducted and represent one of the most effective forest policy mechanisms at regional level.

Beside general guidelines for sustainable management and conservation of biodiversity of forests in Europe following resolutions are considerable concerning climate change in the context of forest and water:

Helsinki (1993) H4: strategies for a process of long-term adaptation of forests in Europe to climate change
Vienna (2003) V5: Climate change and sustainable forest management
Warsaw (2007) W2: Forests and Water

During the last FOREST EUROPE Ministerial Conference in Oslo (2011) on the initiative of Austria the European ministers made an historical decision and launched negotiations for a Legally Binding Agreement on Forests in Europe.

EU Forest Strategy, 2013

The Forest Strategy of the European Union is intended to supplement the national forest policies of the individual member states and to optimize the implementation of community measures in the area of forestry. The Forest Strategy stresses the principle of subsidiarity as well as sustainable management of forests (especially in view of the fact that the amount of wood used for energy production in the EU in 2020 would be equivalent to current total wood harvest) and their multi-functional role as the most important maxims in trade (Rappold, 2007).

The EU Regulation on “support for the development of rural areas” is a framework regulation for the bilateral support between the European Commission and the EU member states aiming at the development of the rural areas. It is including sustainable management considering international agreements, especially the resolutions of the Ministerial Conference for the Protection of Forests in Europe.

Each Member State should point out its intentions to increase forests´ mitigation potential through increased removals and reduced emissions on the one hand and on the other forests ´adaptive capacity to climate change. Also the forest cover should be protected to ensure soil protection, water quality and water quantity regulation by integrating sustainable forestry practices in the Programme of Measures of River Basin Management Plans and in the Rural Development Programmes.

In Austria the EU Resolution currently in force with the “Rural Development Programme” is being implemented, which will terminate on the end of the current year. For the new programme-planning period (2014–2020) a new resolution on support for the development of rural areas will be passed.

Alpine Convention, 1995

The Alpine Convention as a convention for the protection of the alpine region was signed by the Ministers for the Environment of the alpine states and the Environmental Commissioner of the European Commission in 1991 as a multilateral treaty according to international law and was passed by the Austrian National Council in 1995 (FLG No 477/1995 – Federal Law Gazette No. 477/1995). Objective of the Alpine Convention is an environmentally compatible use of the entire alpine region in an economically, ecologically and socially balanced way.

The protocols regarding “conservation of nature and landscapes”, “mountain farming” “land-use planning and sustainable development”, “mountain forests”, “tourism”, “soil conservation”, “energy”, “transport”, as well as a protocol on the settlement of disputes entered into force in 2002. The protocols to the Alpine Convention are part of the Austrian body of law and are thus to be implemented by the legislature and by the law enforcement bodies (Rappold, 2007).

In the context of our project the most interesting protocol is the “Mountain Forest Protocol”. Some statements in this connection: forest regeneration with site-specific tree species, careful harvesting procedures, ensuring its effect on water resources and climate regulation as well as biodiversity.

As the global climate change is effecting the Alpine Space in a notable manner the Alpine Convention emphasises inter alia the importance of strategies on the one side for the adaptation to changes in water balance due to the increase of heavy rainfalls and drought periods and on the other side for the solution of conflict of different targets in water utilization. During the 10th Alpine Conference (Evian, 2009) the “Action Plan on Climate Change in the Alps” was adopted. Main objectives concerning mountain forests are: adaptation to climate change by keeping the Alpine forests in a good ecological state and by increasing their biodiversity, forestry in terms of an economic development of local populations and reinforcement the role played by the forests in preventing natural hazards as well as the implementation of the WFD.

4.7.2 National Legislation

Austrian Water Law 1959 (amendment 2013)

In general, the Austrian Water Law was designed to guarantee continuous provision with water as well as to safeguard future water supply. Therefore it especially regulates the use of water respectively the authorisation of use of water, the protection of water resources and against floods and common water management obligations (water management plan, framework regulations, and programs of the EU).

The WFD was implemented in the amendment in the year 2003. In 2006 the statutory provisions on monitoring systems were implemented with the introduction of the act on water condition monitoring and the Austrian water monitoring systems were adapted. Furthermore, a National Water Management Plan has to be compiled and published by the Federal Ministry of Agriculture, Forestry, Environment and Water Management every six years. In the National Water Management Plan the targets and measures taken to achieve these targets are formulated on the basis of an actual state analysis; it was sent to the EU Commission in 2010. Austria shares three international river basins, namely the Danube, the Rhine and the Elbe, with neighbouring states and has conducted an economic analysis for its fractions of the Danube and the Rhine (since the Elbe river basin in Austria is only of marginal size, no separate analysis was done for this river) (Cencur Curk and Bogardi, 2012).

The central elements of the 2003 amendment of the Austrian Water Law Act are (Cencur Curk and Bogardi, 2012):

- Establishment of requirements for the formulation of environmental goals, such as the “good ecological and chemical condition” for surface waters and the “good chemical and quantitative condition” of ground water;
- Establishment of deadlines for achieving objectives, including the requirements for the gradual implementation of the WFD;
- Establishment of necessary measures to prevent the deterioration of all water bodies and establishment of requirements for deviation from these measures within the authorisation process;
- Establishment of the foundations for a common data information system (WISA – Austrian supra-regional water information system) as a basis for status analyses and the implementation of integrative programmes for the collection of emission data;

- Establishment of administrative requirements for management plans, regional programmes and the active participation of the population;
- Explicit establishment of the combined (integrative) approach;
- Establishment of regulations for the utilisation of economic tools.

One objective of the Austrian Water Law Act consists in establishing a legal framework as a basis for sustainable and responsible use of water resources. Thus there are regulations for the different users: households, the municipal sector, the industrial and services sector (especially power generation) and agriculture.[1]

Agriculture:

- Quality targets and threshold values for nitrate and pesticides were specified by decree in 1991.
- For the purpose of implementing the Nitrates Directive, the Nitrate Action Plan was introduced to reduce the pollution of surface and ground water, e.g. by regulating fertilisation.
- Additionally, the Water Law Act contains regulations for the protection of polluted water bodies. In case of major impacts on water bodies the law also foresees the duty of approval for certain activities, such as the insertion of pollutants into water bodies, activities that may result in contamination of groundwater, large-scale livestock breeding and the use of fertilisers on productive land.
- Regulations on husbandry in water protection areas may contain additional rules or prohibitions.
- Furthermore, the Austrian Agro-Environmental Programme ÖPUL contains a variety of measures for water protection on a voluntary basis. ÖPUL is an element of the programme for rural development which aims at creating incentives for the introduction or preservation of production methods that are compatible with nature protection, conservation of natural resources and biodiversity, promotion of eco-friendly, responsible agriculture, as well as promotion of the inclusion of environmental planning into agricultural practice.
- Finally, the Pflanzenschutzmittelgesetz (plant protection chemicals act) contains a list of prohibited substances, which also has an impact on the targets of the Water Law Act.

Municipal sector:

- The Water Law Act also provides the legal framework for water supply and waste water services (duty of approval, current standards, examination).
- Emission standards and threshold values are included in the first municipal waste water emissions directive, which also holds regulations for water facilities (depending on their size). Water supply facilities are by law subject to approval.

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[1] EU Wasserrahmenrichtlinie 2000/60/EG. Österreichischer Bericht über die IST – Bestandsaufnahme, 2005: 22f

- Regulations for water protection areas also have an impact on municipal water supply; and they may as well contain additional rules for single households.

- The Umweltförderungsgesetz ("Law on the Promotion of Nature and the Environment") regulates the public funding of sanitary environmental engineering projects, aiming at the best possible result in regard to nature protection. The approval of subsidies has as a prerequisite the ecological compatibility and practicability of the project as well as its orientation towards public interests.

- The federal states' tariff regulations along with canalisation and water connection regulations also have an impact on the implementation of the Water Law.

Industry and services:

- The 1990 amendment of the Water Law set standards in regard to waste water discharges for the industrial and services sector as well as for municipalities. The precautionary principle was established by law and foresees adaptive measures to minimise the discharge of waste water and according to current technical standards. Over 60 branch-specific regulations were issued which define these standards as well as monitoring methods, threshold values, and rules for the adaptation of older structures, including a timetable for the respective transition periods.

- Direct wastewater discharges which cannot be considered minor are subject to approval according to article 32 of the Water Law Act.

- Duty of approval also exists for indirect discharges in case of waste water discharges from certain origins or in amounts that exceed threshold values.

- Further regulations for the industrial sector and services originate in the nature protection acts of the federal states.

Power generation:

- The duty of approval in regard to the utilisation of water bodies for power generation is specified in article 9 of the Water Law Act. As stated in the amendment of 2003, the ecological condition of water bodies has to be considered in this course and water usage has to be limited as to preserve the ecosystem's functions.

- Further regulations with an impact on power generation consist in the nature protection acts of the federal states and the EIWOG (Electricity Industry and Organisations Law Act) which regulates the principles of power generation, transmission and distribution.

- The Eco Electricity Act was introduced to promote power generation from renewable sources.

While the worthiness of protection of water bodies is satisfactorily defined in the Water Law, the Austrian National Environment Plan still identified gaps in the practical application of protective measures. Since utilisation demands have increased the strain on water bodies in certain Austrian regions, groundwater protection should be given the highest priority and applied extensively (CC-WaterS, 2012).

Austrian Food Safety and Consumer Protection Act, BGBl 13/2006 (amendment 2013)

Principles and requirements concerning water for human use and the putting into circulation of drinking water respectively hygienic issues are regulated in this law. The Austrian Food Code and the codex-commission define the common requirements concerning the quality of the drinking water.

Austrian Drinking Water Decree, BGBl 304/2001 (amendment 2012)

Decree of the federal minister on the basis of the Food Law - Lebensmittelgesetz (LMG) 1975; regulates the requirements concerning the quality of water for human use, the comprehensiveness and the frequency of drinking water analysis for water suppliers, as well as derogations.

Austrian Guideline ÖVGW W 72 "Water protection and conservation areas", 2004

The purpose of this guideline is to guarantee the quality and quantity of groundwater for the purpose of drinking water supply from planned or existing spring captures by preventive measures in a sustainable and precautionary manner. It serves as a support for the designation of protection and conservation areas taking account of all currently known potential hazards.

This guideline differentiates between three zones (I – capture zone, II – inner protection zone with 60-day-residence-time of water, III – outer protection zone, 360-day) for the protection against pollutions and disturbances of water quantity around the spring capture. Beside land use and management restrictions respectively prohibitions sufficiently large-sized protected areas are inevitable to ensure the sustainable conservation of groundwater. In karst areas vulnerability and risk assessment mapping according to actual scientific methods are recommended.

Substantial importance has itself the constant monitoring of protected areas by the water suppliers, because due to experiences the relevant owners do not respect the guidelines every time or even do not know them.

Austrian Federal Forest Law, BGBl. Nr. 440/1975 (amendment 2007)

Maintaining forests and their multifunctional effects through a sustainable form of forest management is the key objective of the Austrian Federal Forest Law. The latter defines the functions of forests as follows: economic function (sustainable production of wood), protective function (natural hazards), recreational function, and the beneficial functions. The beneficial functions comprise the protection of water, air and climate. These functions are marked in the Forest Development Plan ("Waldentwicklungsplan"). In the Technical Forestry Plan ("Waldfachplan") a detailed management plan can be emphasized.

Concerning the forest related protection of drinking water the most important issues respectively statements are:

- To achieve the objectives of the forest spatial planning forest stands with protection and welfare function, e.g. areas of important water reservoirs, due to the Forest Development Plan (Waldentwicklungsplan) should have an appropriate spatial structure.

- planning of afforestations for the improvement of water balance, especially in areas with only rare forest stands

- obligation to reforestation of deforested areas with appropriate local species

- prohibition of any forest devastation (i.a. incorrect manuring, any immissions, waste disposal); in the course of extensive endangerments of forest stands due to game the responsible organ of the forest monitoring authority have to elaborate an expertise for the hunting authority as well as the head of the forest monitoring authority of the provincial government about reason, nature and scope of the endangerment and proposals for improvement.

- forest clearing of more than 1000 m² needs an approval

- For the protection of water resources “site protective forests” (Standortsschutzwälder) can be designated by a notification of the relevant authority considering public interests versus economic disadvantages due to certain prescriptions and restrictions concerning forest management measures.

- wood harvesting and transportation should be conducted carefully considering the forest soil and vegetation

- prohibition of clear-cuts, which damage the water balance of the forest soil and clear-cuts of more than 2 ha

- clear-cuts of more than 0,5 ha require an official permit

Environmental Impact Assessment Law, 2008

Concerning forest related issues only following issue is mentioned in this law: Certain forest clearances need an Environmental Impact Assessment to analyse the impacts on inter alia climate.

4.7.3 National Strategies, Plans and Programmes

Austrian Adaptation Strategy (AAS), 2012

This strategy was adopted by the Ministerial Council on October 23rd, 2012.

Overall aim:

- to reduce anticipated negative impacts of climate change on Austria's society, economy and nature/ecosystems

- to use positive effects of climate change and promote synergies

- to provide an overall framework in which adaptation should take place - this should ensure coordination and harmonisation of the various climate change adaptation activities

Austria has elaborated this National Adaptation Strategy in the course of a process starting in 2007.

Representatives of public administration and sector policy makers, NPOs and NGOs, the private sector as well as research were actively involved in a participatory process accompanying the development of the Austrian Adaptation Strategy (AAS).

The AAS encompasses two major documents: the general adaptation framework (“Kontext”) and a catalogue of adaptation options for 14 sectors/themes (Action-Programme, NAP): agriculture, forestry, water, tourism, energy – focus electricity, natural hazards, housing and construction, civil protection, health, ecosystems and biodiversity, transport infrastructure, spatial planning, economy and urban green.

Austrian adaptation options have been developed beyond generic recommendations and include specific information for implementation such as responsibilities, existing instruments to be used for mainstreaming adaptation, time frame for implementation, and required resources, etc. Thus, this approach provides measures and information on existing instruments which can be entry points for adaptation in terms of climate proofing, and highly supports implementation.

The current AAS provides a suitable framework for an on-going process of adapting to climate change impacts. It represents a first cornerstone in the Austrian national adaptation process and needs to be further developed at regular intervals in accordance with actual developments, (policy) requirements and gains in knowledge, in the sense of a “living document”. Regular assessments of the progress of adaptation will be carried out. The Ministry of Agriculture, Forestry, Environment and Water Management will initiate and coordinate these evaluation processes. A first implementation report will be presented by the end of 2014 (further reporting is foreseen in a three-year cycle).

National Climate Strategy, 2007

Within the framework of the Kyoto Protocol Austria undertook the commitment to reduce the emissions of greenhouse gases during 2008-2012 to 13% in comparison to the level of the year 1990. Therefore a Strategy to reach this target had to be elaborated. 2012 a comprehensive evaluation was conducted by the Austrian Environment Agency (Umweltbundesamt). This study reveals that Austria did not get much closer to the Kyoto target in recent years despite the implementation of several climate protection measures. As a consequence the Strategy had to be adopted and further measures were elaborated together with experts during various working group meetings.

The focus was laid on efficient energy technologies (thermal renovation of buildings, attractiveness of bicycle-, foot traffic and public transport) and renewable energies (biomass for heating and electricity, solar collectors, district heating, wind power), taking account of regional available resources, and the promotion of the development of new technologies to reduce greenhouse gas emissions on the one hand and to stimulate employment and economic growth on the other hand. To give the climate policy more attention and acceptance, additional activities are proposed - in addition to the adaptation measures - that can be implemented quickly and have a high signal effect.

Austrian Forest Programme, 2005

The Forest Programme has been elaborated by the participants of the Austrian Forest Dialogue, an open forum for all forest relevant interest groups. The derived Work Programme is a document; its measures are continuously updated and further developed. The 7 main thematic areas are related to the 6 "pan-European Criteria for Sustainable Forest Management" of the Ministerial Conference on the Protection of Forests in Europe (MCPFE). The 7th thematic area has been added additionally.

The 7 thematic areas are (Rappold, 2007):

1. Contribution of Austrian forests to climate protection
2. Health and vitality of Austrian forests
3. Productivity and economic aspects of Austrian forests
4. Biological diversity in Austrian forests
5. Protective functions of Austrian forests
6. Social and national economy aspects of Austrian forests
7. Austria's international responsibility for sustainable forest management

Concerning the "climate change issue" (thematic area 1) following measures are proposed:

- Development and implementation of a recognised monitoring system
- Strengthening climate impact research of regional evidence and soil research related to carbon sinks
- Development of adequate adaptation strategies for forest stands (scenario-related basic research, development of technical knowledge, counselling and promotion - with regard to silvicultural and forest protection measures in particular)
- Reduction of emissions of climate-related gases in all fields, especially by imposing the state-of-the-art and paying special attention to the implementation of the Austrian climate protection strategy
- Adequate strategies for the best possible substitution of fossil fuels and raw materials for renewable raw materials (biomass in particular[2])
- Evaluation of possibilities for accounting carbon storage in wood products: Elaboration of accounting rules in the international context

Related to the "Protective function of forests" (thematic area 5) following issues are mentioned:

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[2] **Remark:** The removal of biomass rich in nutrients (needle and leave mass, small branches) has an adverse effect especially on sensitive sites (e.g. with shallow, sandy soil) and can result in considerable increment losses. [BMLFUW: The Austrian Forest Programme, 2007; S. 40]

Due to forest management developments over time and air pollutions accompanied by acid depositions soils were strongly impaired and thus contribute to a reduced vitality of forest stands. Therefore the Advisory Board on soil fertility and protection of the Ministry elaborated guidelines for the maintenance and restoration of soil conditions corresponding to their site-specific circumstances and their respective “potentially natural forest community” (PNFC). In particular, this means a balanced base budget, a functioning nutrient cycle and an adapted humus condition; and includes also a widely closed vegetation cover close to PNFC and multi-storied stand structure in order to reduce erosion and soil impoverishment(Rappold, 2007).

The importance of forests for regular spring intensity with highest quality and a balanced run-off into rivers is highlighted. During respectively after strong precipitation events only low or no run-off of surface water can be observed in forest stands.

Also the function of forests as a worldwide and local climate regulator is emphasised. Due to differences in temperature between forests and urban areas a continuous exchange of air is guaranteed.

For the maintenance of these protective forest functions some necessary measures like forest-pasture-separation and forest-game related problems are mentioned. Concerning the importance of forest and water the evaluation of forest-water interactions as well as the development of adequate strategies considering the WFD is recommended.

Austrian Natural Forest Reserves Programme, 1995

With the signing of the Helsinki-Resolution 1993 Austria promised the implementation of a network of Natural Forest Reserves. Target of this Resolution is the maintenance and improvement of forest-biodiversity. This obligation is also mentioned in the “Mountain Forest Protocol” of the Alpine Convention. Since the beginning of the forest reserves programme a total amount of 200 reserves with approximately 8600 ha were contractually secured. The goal of the Natural Forest Reserves programme is the creation of at least one representative for each forest reserve per forest community and the growing region. Thereby the maintenance and development of natural forest communities should be supported.

The only anthropogenic impact, which is allowed and necessary, is the game regulation by means of hunting measures.

This programme shall provide new knowledge for science and research (basic research) concerning the development of ecosystems and the networking with other research areas for an ecologically oriented, natural forestry. The vulnerability or adaptability of forest ecosystems to potential climate changes is a new important field for further studies.

The success of this programme is based on the involvement of all stakeholders just from the beginning of the process.

Austrian National Environment Plan, 1995

This concept was the first step to intensify the discussion about sustainable development in Austria and the attempt to integrate environmental issues into all levels of policy. Therefore long-term oriented targets and standards for Austria were defined to initiate an environmentally suitable development and additionally the required structural change. A catalogue for the realization of necessary measures in this context was prepared. Unfortunately a systematic implementation, evaluation as well as updating of its targets and measures have not yet been carried out. Only in some parts an implementation within the framework of the Austrian Strategy for a Sustainable Development (NSTRAT) and of already existing sectoral programmes (e.g. Austrian Climate Strategy) is taking place.[3]

General targets for “Agriculture, Forest and Water” are:

- Maximal conservation of resources taking account of natural production forces and regulation mechanisms
- Minimization of ecological risks in terms of sustainability
- Minimization of inputs trough enhancement of energy efficiency as well as closure of material cycles (internal, regional, international)
- Concerning “Forest” following objectives are mentioned:
- Maintenance, support and regeneration of stability of forest ecosystems by means of adapted forestry as well as implementation of required remedial measures if necessary
- Consideration and coordination of different landuse requirements trough priority-setting, balance of interests and building compromise
- Maintenance, regeneration or establishment of forests with internal and external stability considering sitespecific conditions
- Forestry as close to nature as possible (e.g. support of “green” logging operations, environmentally friendly road-construction methods)
- Hunting measures based on ecological criteria
- Segregation of forest and grazing areas
- Training, information, advice, awareness raising of stakeholders and financial subsidies for affected forest owners

Furthermore the guarantee of drinking water in a qualitative and quantitative manner is highlighted. Some issues have to be researched: material balance – strategies for minimization of emissions from forestry, site-related classification and typing of ecosystems as well as their comprehensive mapping,

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[3] BMLFUW: The Austrian Forest Programme, 2007; p. 20

preparation of principles for the analysis of life-cycles of forest products, research of responsiveness and dynamic reaction of ecosystems towards external impacts.

National Water Management Plan, 2009 (NGP – Nationaler Gewässerbewirtschaftungsplan)

All those interested in the protection and further development of waters, but also all those affected by management measures on waters were actively involved in the planning process. Comments and suggestions were included and in March 2010 the "National Water Management Plan 2009“ was published. The plan is applicable for six years and contains concrete targets until 2015. Afterwards it will be evaluated and an updating with a view to medium-term and long-term planning of objectives and measures will be carried out every six years.

The major problem concerning groundwater is the pollution with nitrate in the eastern part of Austria. Till 2015 these values have to be reduced by means of current measures according to the "Action Programme Nitrate", various plant protection provisions and the intensive subsidisation programme within the framework of rural development.

Even though no major effects are expected as a result of climate change, it is important to monitor water bodies permanently in order to be able to respond to changes in due time.

In 2010 the Ministry of Agriculture, Forestry, Environment and Water Management (BMLFUW) together with the Federal Provinces commissioned a study on strategies for adapting to climate change for Austria's water management sector from the Vienna University of Technology.

Concerning "Groundwater-issues" following theses are mentioned: For the south of Austria, where precipitation is expected to decrease in winter, and for the low-precipitation regions in the eastern parts of Austria, groundwater recharge will probably decrease again in the future. In the north and west of Austria, groundwater recharge might increase.

Due to the noticed rise in temperature of surface and groundwater the processes occurring between these systems take place a little more rapidly and completely, which may lead to changes in the chemical composition. Therefore the existing groundwater protection policy should be continued.

Because of Austria's abundance of water and the minor changes to be expected, large-scale shortcomings of drinking water are not probable; nevertheless bottlenecks in areas with unfavourable water supply conditions might intensify. This has to be taken into account in the management of Austrians water resources (further development of water–saving technologies, industrial process water systems, awareness raising).

Subsidy programme ‚Forest for Water' (FWW - Förderprogramm "Wald für Wasser")

As part of the EU Rural Development Regulation in addition to a variety of other measures also the tending and restoration of forests with protection-, welfare- and recreational effect are financed. In this context the best possible securing of public service functions of the forest - especially the protection and water storage capacity - is gaining an increasing importance.

Taking account of this development, the Forestry Department of the Ministry of Agriculture, Forestry, Environment and Water Management (BMLFUW) plans in addition to the program "Protection trough Forest" (in VOLE 07-13: ISDW) the implementation of a further module "Forest for Water" - on the one hand to improve the forest effects on the water regime and on the other hand to clean up ditches and riverside forests.

Both of the subsidy programmes (ISDW and FWW) are an initiative of the BMLFUW in cooperation with the Federal Research and Training Centre for Forests, Natural Hazards and Landscape (BFW), the regional headquarters of the Forest Engineering Service in Torrent and Avalanche Control (WLV), the Institute for Silviculture of the University of Natural Resources and Life Sciences (BOKU) as well as federal and province services.

The conception of the program "Forest for Water" (FWW) is the result of further development of the experiences already carried out by restoration and tending concepts in the context of the program "Protection trough Forest" (SDW).

The targets of this subsidy programme are:

- The preservation and improvement of preventive protection effect of forests with object protection against natural hazards as well as the hydrological optimization of forest management in order to maintain and improve the continuity and quality of spring water and groundwater.

- The improvement of the structural, physical and ecological stability of the protection-relevant tillering respectively of their resistance to biotic and abiotic factors.

- The extension and accelerated, timely acquisition and treatment of such forests. This will particularly apply to those areas that can be improved predominantly with silvicultural measures and accompanying simple technical measures, needed to secure the success of silvicultural measures.

This new programme shall secure drinking water resources for future generations by means of adjusted forest management measures. To compensate the following additional expenses subsidies within the framework of the Regulation “Rural Development 2014+” could be distributed considering already existing requirements by the Austrian “Water Law Act” or other legislative rules and guidelines. To avoid any duplicate funding existing subsidies must be considered in the run-up.

Due to the long implementation periods the measures, which will be supported by the VOLE-programme (2014-2020), have to be seen only as an initial step towards the desired state improvements.

The basis for the study area concerning FWW provide the “Forest Development Plan” (forest functional areas of the WEP), the torrential catchment areas and the water protection and conservation areas.

First of all the range of supports has to be defined. Based on the “District Framework Plan” (Bezirksrahmenplan), which is prepared according to the “Forest Development Plan”, planning areas for potential detail-projects focused on vulnerable ditches, water protection and conservation areas as well as catchment areas of springs have to be displayed by the Forestry Authority together with Water and River Engineering Authority as well as the Forest Engineering Service in Torrent and Avalanche Control and the Water Associations / Waterworks.

Within the detail-projects the actual situation of the surface (relief, roughness, geology, hydrology, soil, humus etc.) and the vegetation (tree species, tree crown cover, percentage of young trees, structure, ground vegetation, game damage etc.) in the affected forest stands has to be surveyed by forest managers, foresters or other authorized persons. These results have to be compared with the optimal condition of forest stands for the protection of drinking water. Consequently the necessary package of measures can be pointed out and the following expenses have to be calculated. Before submitting a request to the relevant funding authorities the declaration of consent of the forest owner is obvious.

The fundamental requirement for all efforts in this context is however the continuous success-controlling of the realized measures.

4.7.4 Regional strategies

Climate Change Adaptation Strategy for Upper Austria (July 2013)

Based on the Austrian Adaptation Strategy (AAS) 2012 also Upper Austria developed a Climate Change Adaptation Strategy. Within this Strategy measure packages – mainly in terms of climate adaptation - are developed for all sectors based on results from several studies in the context with climate change.

Concerning “Forest Management” following measures are mainly mentioned:

- Information and support (with 100 demo-spaces and “journey to the climate change”) of the stakeholders
- Incentives for forest owners
- Brochures with recommendations concerning tree species taking account of climate change
- Funding of mixed forest stands trough conversions and reforestation after disaster events
- Pilot actions with choice of suitable sources (e.g. oak)

4.8 References

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5. Annex 2

Modelling climate change impacts on nitrate loss in a managed forest

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5.1 Abstract

Forest management and climate change directly or indirectly affect forest dynamics and thereby exert impacts on karst water resources, both in terms of quality and quantity. In this study we choose model calculations (Landscape-DNDC) in order to resolve the complex long-term interactions of management and climate change on tree growth and nitrogen dynamics, and consequences for nitrate leaching from forest soils into the karst groundwater. Our study exemplified the dominant role of forest management in controlling nitrate leaching. Both clear cut and shelterwood cut disrupt the nitrogen cycle to an extent that causes peak concentration and fluxes in the seepage water. This effect is well known. However, additional impact was apparent which is related to expected climatic changes. First, our modelling approach showed that peak concentration and fluxes of nitrate were even higher during post-cutting periods. Second, higher temperature and less precipitation in summer impeded growth of young Norway spruce trees. As a consequence, nitrogen uptake was lowered and nitrate loss more severe. Third, growth was stimulated later on in mature trees by higher temperatures causing high uptake of nitrogen and less leaching in all climate scenarios as compared to the baseline. Under all management options, climate change lowered cumulative nitrate losses over full forest rotation periods. This improvement was highest in continuous forest cover management while conventional management subdued the positive effect of climate change to nitrate loads leaving forest soils.

Keywords

Ecological modelling; LTER Zöbelboden; forest growth; drought effects; European Alps

5.2 Introduction

About 15 % of Austria’s total area is karstified (Trimmel, 1998) and its karst catchments provide half of the water supply for the Austrian population. Due to a short residence time of part of the karst water the filtering and transformation capacity in vegetation and soil are of ultimate importance for the quality of karst spring water. Large karst areas are located in the Northern and Southern Limestone Alps, where in the montane and subalpine life belt forests are the dominating land cover. Though nitrate pollution of drinking water is usually attributed to fertilization of crops and grassland, an excess input of atmospheric nitrogen from industry, traffic and agriculture into forests has caused reasonable nitrate losses in forest areas(Erisman and de Vries, 2000; Gundersen *et al.*, 2006; Butterbach-Bahl and Gundersen, 2011; Kiese *et al.*, 2011). The Northern Limestone Alps area is exposed to particularly high nitrogen deposition(Rogora *et al.*, 2006) and nitrate leaching occurs in increased rates(Jost *et al.*, 2011). Combined effects with climate change can be expected because in the respective forest ecosystems nitrate loss with seepage water is tightly linked to snow melting and rainfall (Kane *et al.*, 2008; Jost *et al.*, 2011).

Forest management and climate change directly (through e.g. tree growth) or indirectly (through e.g. bark beetle damage) affect forest dynamics and thereby exert impacts on karst water resources, both in terms of quality and quantity. Forests play an important role as they stabilize the fragile soil and humus horizons(Christophel *et al.*, 2013) which dominate the Northern Limestone Alps and, when managed appropriately, keep water pollution at a low level(Katzensteiner, 2003; Weis *et al.*, 2006). However, the establishment of homogeneous Norway spruce plantations created forest stands which are vulnerable to wind throw and bark beetle infestations, thus will face enhanced risk under future climate change (Seidl *et al.*, 2011). Most of these forests are managed with clear-cuts or shelterwood-cuts in order to maximize economic return. Trees accumulate nitrogen in their biomass and lose nitrogen via above and belowground litter fall. Trees also control the microclimate of soils, and thereby act upon nitrogen turnover(Butterbach-Bahl and Gundersen, 2011). Tree harvest hence exerts a strong control over nitrogen cycling but also to the loss or accumulation of soil organic matter. Forest management may cause severe nutrient and humus losses from the soils, which may lead to a partial loss of soil functions (Katzensteiner, 2003; Christophel *et al.*, 2013). Clear-cut disrupts the nutrient cycle so that nitrate is mobilized and washed out from the soils. Typically this happens only over a few years after the event (Katzensteiner, 2003; Gundersen *et al.*, 2006; Weis *et al.*, 2006). In managed forests, tree species choice also influences nitrate leaching. Coniferous trees such as Norway spruce (*Picea abies* L.) intercept more nitrogen from the atmosphere and these forests show higher nitrate concentration in the seepage as compared to mixed or deciduous forests (De Schrijver *et al.*, 2007; Jost *et al.*, 2011). Forest management concepts for water protected areas therefore focus on the prevention of clear-cut phases and recommend a close to natural mixture of tree species, single tree or group selection cuts, or continuous cover forestry.

Though reasonable knowledge exists as to the effects of forest management to nitrate leaching, the effects of climate change remain rather obscure (Bernal *et al.*, 2012). For the Northern Limestone Alps area downscaled A1B, A2 and B2 scenarios predicta temperatures increase of approx. 2-5°C by 2100, whereby the increase may be stronger during summer. Precipitation may increase in winter and may decrease in summer(Loibl *et al.*, 2011; Ahrens *et al.*, 2014). Since nitrate leaching depends on the amount of seepage waterless precipitation and higher temperatures and thus evapotranspiration during summer should decrease leaching rates. However, temperature increase will affect tree growth and thereby controlling the uptake of nitrogen. In a recent study carried out in the Northern Limestone Alps, (Hartl-Meier *et al.*, 2014a) showed, that Norway spruce is drought sensitive at the lower montane and montane belt with a negative growth response to temperature. But they also found that increased temperature increases growth at higher altitudes. For beech, the relationship between growth and temperature also depended on altitude, but there was no clear drought sensitivity. These species specific growth responses have been shown in many other studies (see citations in Hartl-Meier et al.(2014a).Temperature together with soil moisture also controls N mineralisation in the soil(Butterbach-Bahl and Gundersen, 2011).Recently, studies on wind throw in limestone areas have shown that drought and nutrient loss (pers. comm. Kohlpaintner, Pröll) suppress the establishment of spruce (. With increasing summer droughts this might result in increased nitrate leaching after overstorey clear-cut. Winter runoff will most probably increase particularly if snow precipitation becomes less frequent. Nitrate export is strongly triggered by snow melt events (Jost *et al.*, 2011) which will potentially increase in frequency and amount. Since nitrogen immobilisation in soils and uptake by trees is low during cold periods nitrate runoff might increase.

We study the explained processes in an intensively observed long-term forest ecosystem research site in the "Kalkalpen" national park (LTER Zöbelboden). We choose model calculations in order to resolve the complex long-term interactions of management and climate change on tree growth and nitrogen dynamics. We used Landscape-DNDC (Landscape-DNDC) as a process based ecosystem model (Haas *et al.*, 2013) in order to follow nitrogen leaching over entire rotation periods of 120 years. Future climate projections were derived for A1B-, A2- and B1-scenarios (Loibl *et al.*, 2011). Three forest management regimes were defined: low (continuous forest cover spruce-beech management), medium (spruce shelterwood management, natural regeneration) and high intervention (spruce clear-cut management, planting).The model was calibrated and validated with long-term measurements of forest growth, soil, soil water and runoff water. Specifically we tested the following hypotheses:

1) Nitrate loss to the groundwater will become less of an issue in general because climate changes will decrease runoff.
2) An increase in temperature will stimulate tree growth leading to higher nitrogen uptake and less nitrate leaching.
3) Summer droughts will become more frequent, thereby suppressing tree growth and increasing nitrate loss.

5.3 Materials and Methods

5.3.1 Study area

The studied forest stand was located within the Austrian LTER site "Zöbelboden" in the northern part of the "Kalkalpen" national park, Austria (N 47°50'30", E 14°26'30"). The long-term average annual air temperature was 7.8°C (1996-2011). Mean annual rainfall between 1996 and 2011 was 1645 mm. Snow cover (> 10 cm) lasted from December to April. The mean N deposition in bulk precipitation between 1993 and 2006 was 18.7 kg $N.ha^{-1}.yr^{-1}$, out of which 15.3 kg N was inorganic (approximately half as NO_3^--N and half as NH_4^+-N)(Jost *et al.*, 2011). The study site is located on an almost flat plateau at ~ 950 m.a.s.l. The study plot (intensive plot I, IP 1) is located on the plateau where Chromic Cambisols predominate with patches of Rendsic Leptosols and Hydromorphic Stagnosols. The mineral soil is a silty clay or silty loam and has a depth of around 50 cm. The pH-value is 5.3 in the humus layer and around 6.5 in the mineral soil. Total carbon sums to 115 tons C ha^{-1}(including litter).

The C/N ratio is around 27 in the humus layer and 17 in the upper 10 cm of the mineral soil(Jost *et al.*, 2011). Mull and moder humus forms predominate. The plot is dominated by Norway spruce following plantation after a clear cut around the year 1910. Spruce has a standing volume of 860 m^3 and European beech (*Fagus sylvatica* L.) has 114 m^3.The plot has been exposed to bark beetle infestation in the year 2004 and onwards. Impaired deposition samplers and lysimeters were excluded from the analysis. Forest management has been restricted to single tree harvesting in case of bark beetle infestation.

5.3.2 The model Landscape-DNDC

Modelling will be done with Landscape-DNDC, which is one of the most elaborated dynamic ecosystem model (Cameron *et al.*, 2013). Within Landscape-DNDC the biogeochemical processes of agricultural DNDC and the Forest-DNDC model (Li *et al.*, 2000) were integrated into a general soil biogeochemistry module (Haas *et al.*, 2013). This enables the simulation of ecosystem C and N turnover and changes in soil C and N stocks for various forest and grassland types. It has been used successfully to model nitrate leaching in a number of sites in southern Germany (Kiese *et al.*, 2011). Landscape-DNDC explicitly accounts for forest management and tree mortality of mixed tree stands with its physiologically based vegetation module PSIM (Grote *et al.*, 2011).

5.3.3. Input data for the model

Climate parameters (i.e. air temperature, precipitation, vapour pressure, solar radiation, windspeed) were recorded in half-hourly intervals at a meadow in close vicinity to the experimental stand since the year 1993 and at a measuring tower of 40 m height. Gap filling was done according to Jost et al. (2011).

Total N, nitrate and ammonia in bulk precipitation, throughfall, and seepage from the soil-bedrock interface into the karst system has been monitored since 1993. Samples were analysed in weekly intervals until 1999. From 1999 onwards, samples from two consecutive weeks were mixed (volume weighted) and analysed bi-weekly. After 2008 four consecutive weeks and monthly sampling was applied(Jost *et al.*, 2011).

Forest stand inventories were conducted in 2003, 2007 and 2012. The position, the height, the diameter at the breast height (dbh; 1.37 m) was measured. Number of individuals per tree species, mean tree and crown height, and mean dbh was used as model input.

Soil data stems from a soil inventory in the year 2005. In the laboratory samples were weighted. Green plant material like roots and grasses were separated, weighted, dried at 30°C until constant weight, re-weighted and stored separately. The remaining material was weighted, dried at approximately 30°C until constant weight, whereas coarse aggregates have been crushed and re-weighted again. The dry soil was sieved through a 2.0 mm sieve and subsequently 10 g of the samples were dried at 105° C until constant weight. In contrast to the mineral soil, the forest floor was milled for 15 minutes before sieving and drying at 105°C.Total content of C (TC) was analyzed by dry combustion (1300°) of the samples in O_2. Released CO_2 was detected coulometrically (StröhleinCoulomat 702 and Si 111/6). Total content of $CaCO_3$ (TIC) was measured via addition of HCl and volumetrically determination of the released CO_2 (Scheibler). Total content of organic C (TOC) was calculated by subtracting the total content of $CaCO_3$ from the total content of C (TC – TIC). Total content of N was primarily determined by a modified Kjeldahl method. The organic N was converted to NH_4^+ by digestion with H_2SO_4 and a catalyst (Kjeldahlterm KT8 Gerhardt). The accumulated

$NH_4^+$was converted to NH_3 (distillation) and measured by potentiometric titration. To account for nitrogen oxygen compounds, salicylic acid was added prior the digestion.

The soil particle sizes were determined by combination of wet sieving of the fraction >2µm and by particle size analyzer (Micrometrics SEDIGRAPH5000ET) for the fraction <2µm. The Sedigraph uses Stokes' Law to determine the settling velocity of particles <2µm and uses an X-Ray adsorption tomeasure the concentration of these particles which fall under gravity through a liquid. Results are plotted on a cumulative curve of the sedigraph data and the sieving data as weight percent. Approximately 50 g of the air dried sample was weighted into a 100 ml jar.200 ml 10% diluted hydrogen peroxid (H_20_2) was carefully added (for proper dispersion and for removing organic matter). After ca. 3-4 days (until no more reaction is observed) reaction time and removal of the remaining hydrogen peroxid the sample was placed into the 950C water bath. The jars are removed from the water bath and cooled. Afterwards they are treated with ultrasound and pass through a series of sieves: 2 mm, 0.630 mm, 0.200 mm, 0.063mm and 0.020 mm. The <20 µm portion was suspended in water, a representative portion was taken out, treated with 0.05% calgon and ultrasound, and analyzed with sedigraph by X-Ray.

Twenty soil samples were analysed to determine the saturated hydraulic conductivity - (Ks) and soilwater retention curve (SWRC) parameters. Saturated hydraulic conductivity was determined using the falling head technique using a KSatInstrument (UMS GmbH, Munich, Germany), which can measure conductivities ranging between 0.01to 5000 cm d^{-1}.Following the Ks measurements, the wet range of the SWRC (0 to 0.06 MPa) of the saturated samples were determined using the Hyprop (UMS GmbH, Munich, Germany) system.The dry range of the SRWC was determined with a WP4C Dewpoint Potentiometer (Decagon Device, Washington, USA) using the subsamples taken during dry weight determination. The results from the Hyprop and WP4C measurements were combined together and analysed with the Hyprop Data Evaluation software (UMS GmbH, Munich, Germany). Using non-linear least squares regression, the software fits the van Genuchten(1980)model and derives the respective water retention parameters.

5.3.4 Data for model validation

The model was validated with tree growth, soil moisture and soil water data.

Temporal dynamics of annual tree biomass of the studied stand were derived from time series of aboveground biomass of 18 trees equipped with dendrometers together with forest inventory data. In 1997, 13 spruce and 5 beech trees were installed with manual DIAL-DENDRO, D1 dendrometer and increment of dbh was measured weekly. The trees present a sound sample to render the temporal dynamics of aboveground tree biomass of the studied plot. The temporal dynamics of the stem biomass of each dendrometer equipped tree has been estimated fromdbh and tree height on the base of an allometric function according to Pollanschütz (see Zianis et al. (2005)). Tree height was estimated from dbh by means of tree-specific dbh/height ratios derived from the forest inventory. Total stem wood biomass of the study plot was calculated with an expansion factor, i.e. the ratio between the stem wood biomass of the trees equipped with dendrometers and the stem wood biomass of the whole plot.

Soil water content was monitored at hourly intervals with time domain reflectometry (TDR) sensors (Jost *et al.*, 2011). We averaged the values of 3 sensors, two positioned at 20 cm and one at 28 cm, in order to compare these with simulated values in the same depth ranges. The averaging was done because reasonable variance occurs between measurements in the same soil depth. Data between 2003 and 2006 was used which was well beyond model warming up and which was not influenced by small scale disturbances in the plot.

Seepage water was collected at the soil-bedrock interface with two clusters, each with 3plate lysimeters. Lysimeters were installed such as to ensure that water samples capture the variability of each plot in respect to soil depths and water-flow pathways. Again, weekly samples were mixed (volume weighted) biweekly. $NO_3^-$was determined by ion chromatography with conductivity detection (Dionex IC System 4000 I until 2002, thereafter with Dionex IC System Serie DX 500, soil water after 2002 was analysed with Metrohm IC System 7xx - Serie).NO_3^- concentration was calculated as a volume weighted average of all lysimeters in a cluster(Jost *et al.*, 2011).

5.3.5 Climate and management scenarios

Future trajectories of daily model-specific climatic parameters (i.e. precipitation, maximum temperature, minimum temperature, humidity, solar radiation, wind speed) for three time slices (2025-2035, 2055-2065, 2085-2095, called 2030, 2060, 2090 thereafter) were derived from simulated synthetic 150 year time series of mentioned climatic parameters of the study site perturbed by parameter-specific climate change anomalies gathered from A1B-, A2- and B1-scenarios(IPCC-SRES, 2000). Simulated synthetic time series of climatic parameters were derived by the weather generator ClimGen (Stöckle *et al.*, 1999) on the base of climatic parameters measured on the study site (see above). As ClimGen proposes a minimum length of time series of precipitation of 25 years, the present time series of precipitation was extended by the measurements of a nearby climate station in the village Reichraming. The length of 150 years was chosen to cover the rotation period of these forests. Parameter-specific monthly climate change anomalies for the study site were derived from the respective grid cell of the realisation of the regional climate model COSMO-CLMfor Austria(Loibl *et al.*, 2011).

Three forest management options were defined with help of the local forest managers: Continuous forest cover spruce-beech management with natural regeneration (CFM), shelterwood-cut management with spruce and natural regeneration(SCM) and clear-cut management with spruce and planting after clear-cut(CCM) (Table 1).

Table 1. Forest management options. CFM: continuous forest cover spruce-beech management; SCM: shelterwood-cut management; CCM: clear-cut management.

	Tree species	Overstoreythinnings	Final harvest	Understorey regeneration
CFM	Norway spruce (50%), European beech (50%)	Target diameter harvest at ~50 cm dbh	No	natural
SCM	Norway spruce (100%)	Thinning to 400 trees.ha^{-1}at 10, 25, 40 years	50% stem reduction at 115 years; total harvest at 120 years	natural(2500 trees.ha^{-1} in 110 years old forest stand)
CCM	Norway spruce (100%)	Thinning to 400 trees.ha^{-1}at 10, 25, 40 years	100% harvest at 120 years	planting (2500 trees.ha^{-1})

5.3.6 Data analyses

Modelled and measured values of stemwood increment as well as nitrate concentrations in seepage water were compared with t-test statistics.

Simulated and observed values of soil moisture were compared with the Kling-Gupta-Efficiency (Gupta *et al.*, 2009) which distinguishes between three criterions: the Pearson product-moment correlation coefficient (r), the ratio between the mean of the simulated values and the mean of the observed ones (β), and the ratio between the coefficient of variation of the simulated values to the coefficient of variation of the observed ones (γ).

To test differences in cumulative leaching over the entire 120 years rotation period we used an ANOVA with F test statistic, where the climate target year was nested in the emission scenario and the management options.

5.4 Results

5.4.1 Model validation

The Landscape-DNDC stemwood increments between 1996 and 2009 were higher (9.3 t.ha^{-1}) than those measured (8.1 t.ha^{-1}) but not significantly (t-test p-value = 0.126).

Fehler! Verweisquelle konnte nicht gefunden werden. shows that simulated soil water values between 20 and 30 cm soil depth reasonably fitted the measurements. The Kling-Gupta efficiency is 0.43 between the years 2003 and 2006. Annual correlation coefficients were >0.6, the total between 2003 and 2006 was 0.55. Mean values are very similar so that β is ~1. Extreme drought situations such as in the years 2003 and 2006 were well captured by Landscape-DNDC (**Fehler! Verweisquelle**

konnte nicht gefunden werden.). The annual biases (γ) were between 0.37 and 0.74. In spring the model predicted soil moisture which was in the lower range or below the measurements whereas in autumn they were in the higher range or above than the measurements (**Fehler! Verweisquelle konnte nicht gefunden werden.**). A rather low bias was apparent when comparing over a number of years (Table 2). Percolation was higher as compared to annual sums reported in Jost et al. (2011).

Table 2.Kling-Gupta-Efficiencyof measured and modelled soil moisture data (20 -30 cm soil depth) for single years and the period between 2003 and 2006.r: the Pearson product-moment correlation coefficient. β: the ratio between the mean of the simulated values and the mean of the observed ones.γ: the ratio between the coefficient of variation of the simulated values to the coefficient of variation of the observed ones.

Year	Kling-Gupta efficiency	r	β	γ
2003	0.60	0,71	0,94	0,74
2004	0.36	0,65	0,99	0,47
2005	0.32	0,74	1,03	0,37
2006	0.36	0,66	1,05	0,46
2003-2006	**0.43**	**0,58**	**1**	**0,61**

Measured nitrate concentrations in the seepage water between 2000 and 2009 averaged to 7.9 mg.l^{-1}. Landscape-DNDC concentrations are slightly but significantly (t-test p-value = 0.073) higher and average to 9.2 mg.l^{-1}(Figure 11). Nitrate fluxes were higher but within the ranges of annual fluxes found in Jost et al. (2011).

We did also compare modelled snow water equivalent with measured snow depth data and found reasonable agreement.

5.4.2 Expected climate change

According to the assumed emission scenarios and the regional climate data annual mean temperature will increase by 2 to 3.8 °C till the end of the century with rather even distribution among seasons (Table 3). In contrast, scenario data shows a decrease of precipitation in summer and an increase in winter with quite some variation among emission scenarios. On an annual basis, no significant changes are expected.

Table 3.Expected annual and seasonal (summer: June – August; winter: December – February) climate change as compared to the current climate (1995-2005).Minimum, mean and maximum temperature change (T in °C) and precipitation change (P in %) at LTER Zöbelboden in B1, A1B and A2 emission scenarios. Derived with the weather generator ClimGen and regional climate model COSMO-CLM data (Loibl *et al.*, 2011).

	Min/**Mean**/Max	Min/**Mean**/Max	Min/**Mean**/Max
	Annual	**Summer**	**Winter**
T 1995-2005	+7.9	+15.8	-0.1
T 2030	0/**+0.5**/ +1.3	+0.1 / **+0.7** / +1.7	-0.7 / **+0.6** / +1.8
T 2060	+0.9/**+1.7**/ +2.7	+1.3 / **+2.0** / +2.8	+1.0 / **+2.0** / +3.2
T 2090	+2/**+3.1**/ +3.8	+2.1 / **+3.4** / +4.7	+2.1 / **+3.3** / +4.0
P 1995-2005	1530	495	321
P 2030	+6/**+0.8**/-2	+8 / **-1** / -7	-9 / **+4** / +21
P 2060	+7 / **+1.8** / -1	0 / **-12** / -18	+3 / **+7** / +9
P 2090	+3 / **-1.5** / -5	-3 / **-11** / -22	-4 / **+5** / +23

5.4.3 Changes in nitrate concentrations and fluxes

The model predicted annual mean NO_3^- concentrations in the seepage water of 7.2 $mg.l^{-1}$ and peak values (mean of the annual 95% quantile) of 17 $mg.l^{-1}$ for the continuous forest cover (CFM) regime, i.e. without major change in the overstorey trees and for the current climate. Running the model with the 2090 climates the concentrations did not change significantly but there was quite some variation among emission scenarios (5.9-8.1 $mg.l^{-1}$for the mean and 16-19.6 $mg.l^{-1}$for the 95% quantile). The same downward trend was found for all management scenarios.

The Landscape-DNDC model predicted seepage water nitrate concentrations > 80 $mg.l^{-1}$after clear-cut whereas without disturbances nitrate concentration was mainly < 20 $mg.l^{-1}$. The climate driven changes in concentrations were the following: peak nitrate concentrations in the seepage increased during clear-cut and thinning under all emission scenarios, but only by ~10-15$mg.l^{-1}$ at the maximum. Also during understorey reinitiation in clear-cut and shelterwood systems nitrate leaching was, in the same magnitude as the peak concentrations, higher as compared to the current climate. In mature forest stands and under SCM and CCM, nitrate concentrations first decreased by ~ 10-15 $mg.l^{-1}$and then converged with the baseline under all climate scenarios.

5.4.4 Cumulative nitrate fluxes

Cumulative nitrate leaching over a 120 years rotation period amounted on average to 2100 kg NO_3^--$N.ha^{-1}$ (sd = 187).The climate scenario years (2030, 2060 and 2090), the management, and the interaction of both had a significant effect on cumulative nitrate leaching (Table 4). The differences between the management regimes were lower than the differences between scenario years, i.e. the strength of climate change. Averaged over all scenarios, cumulative fluxes were continuously decreasing from the baseline to the year 2090 by 196 to 309 kg NO_3^--$N.ha^{-1}$.Significant differences (Tukey post hoc test)were only found for CCM-2090 (p value 0.008), SCM-2090 (p value <0.001), CFM-2060 (p value 0.002) and CFM-2090 (p value <0.001).So the effect of climate change on nitrate loss was more pronounced in CFM – less nitrate leaching occurred – as compared to CCM and SCM. Whereas fluxes of nitrate to the groundwater were higher under SCM and CCM management after clear cut andduring initiation of the new forest stands as compared to CFM management, they converged towards the end of the rotation period (Figure 12). The difference between CFM as compared to CCM and SCM did increase with strength of climate change (Figure 12) but significant differences (Tukey post hoc test) were only found for the scenario year 2090 (p values 0.03 and <0.001).

Table 4. Significance in differences in cumulative nitrate leaching rates between the baseline (2005) and three different scenario years (2030, 2060, 2090) and three management practices (CFM: continuous forest cover spruce-beech management;SCM: shelterwood-cut management; CCM: clear-cut management) in threeemission scenarios (B1, A1B with two models and A2).

Variable	df	Mean square	F test statistic	p-value
Scenario Year	3	1122161	43.4	<0.001
Management	2	200516	7.8	<0.001
Scenario Year x Management	6	82240	3.2	0.005
Residuals	192	25854		

5.5 Discussion

Our study exemplified the dominant role of forest management in controlling nitrate leaching. Both clear cut and shelterwood cut disrupt the nitrogen cycle to an extent that causes peak concentration and fluxes in the seepage water. This effect is well known. However, additional impact was apparent which is related to expected climatic changes. First, our modelling approach showed that peak concentration and fluxes of nitrate were even higher during post-cutting periods. Second, higher temperature and less precipitation in summer impeded growth of young Norway spruce trees. As a consequence, nitrogen uptake was lowered and nitrate loss more severe. Third, growth was stimulated later on in mature trees by higher temperatures causing high uptake of nitrogen and less leaching in all climate scenarios as compared to the baseline. Under all management options, climate change lowered cumulative nitrate losses over full forest rotation periods. This improvement was highest in continuous forest cover management while conventional management subdued the positive effect of climate change to nitrate loads leaving forest soils.

5.5.1 Nitrate leaching after tree removal

It is well known that nitrate leaching to the groundwater increases sharply after clear cut in forests where nitrogen is not strongly limited(Weis *et al.*, 2001; Katzensteiner, 2003; Huber *et al.*, 2004; Weis *et al.*, 2006; Griffin *et al.*, 2011). Reasonable nitrate leaching occurs during this phase and may contaminate the groundwater. The Landscape-DNDC model showed that seepage water nitrate concentrations reached > 80 mg/l after a total clear-cut whereas without disturbances nitrate concentration is mainly < 20 mg/l. These values are in the range of the above studies and are comparable with measurements at the site (Jost *et al.*, 2011).Usually, seepage water undergoes natural attenuation in the epikarst and the karst conduits by e.g. immobilization in biofilms (Wilhartitz *et al.*, 2009)and mixing with older water(Einsiedl and Mayer, 2006). At Zöbelboden, nitrate concentration in the spring-water remained below 10 mg/l since 1992 and did not exceed 15 mg/l after wind throw of about 10% of the catchment (unpublished data). Albeit concentrations are not above EU drinking water regulations, the loads are reasonable due to high precipitation leading to diffuse increase of nitrate in the groundwater (Kiese *et al.*, 2011).

Peak concentrations and fluxes after overstorey tree removal increased in all climate scenarios. Clear-cut disrupts the nutrient cycle so that nitrate is mobilized and washed out from the soils. Typically these effects are strongest during only a few years after the event (Katzensteiner 2003; Weis et al. 2006). Peak nitrate leaching was only to some extent due to the dominant role of hydrology in driving nitrate leaching as shown in Jost et al. (2011). Depending on the strength of the climate scenario either increased nitrification or percolation was the dominant driver. Under the 2030 climate projections higher winter rainfall and only moderate decrease of summer rainfalls led to an increase in annual precipitation. As a result, percolation was higher in comparison to the baseline and thus nitrate leaching was also higher after clear-cut. High nitrate pulses may mostly be due to increasing precipitation during winter. Snow accumulation and subsequent melting events controlled most of the annual nitrate loss rates in the study site(Jost *et al.*, 2011). The combination of lower annual precipitation, driven by a decrease in the summer season, and higher temperature with increased evapotranspiration in the 2090 scenarios lead to low percolation in all model runs. However, net nitrification increased and percolation after clear-cut, when no tree transpiration occurs, was still high so that the net effect on nitrate leaching was positive. Since soil moisture remained in a favorable condition for nitrification and $NH_4^+$was not limited owing to high amounts of atmospheric deposition, temperature remained as the main control upon nitrate production and leaching.

It was surprising that the effect of climate change to peak concentrations and fluxes were not much different between clear-cut and shelterwood-cut management. However, our management scenario assumed that 50% of the trees were removed, which reflects management interventions that are typical. Other studies used 20-30% removal and reported significant differences as to subsequent nitrate leaching (Weis *et al.*, 2001; Huber *et al.*, 2004; Weis *et al.*, 2006). Uptake of nitrogen through either a dense layer of vascular plants or through tree regeneration plays an important role in lowering nitrate loss (Weis *et al.*, 2001). Though understorey trees were initiated prior to overstorey removal in our model, their development is hard to model and N uptake may therefore be uncertain. Also forest floor vegetation is not addressed in the model.

5.5.2 Nitrate loss during understorey reinitiation

The regeneration phase plays an important role in maintaining stability of mountain forests (Dorren et al. 2004). With understorey trees developing after clear cut or wind throw, peak flows of nitrate cease within a couple of years (Katzensteiner, 2003; Gundersen *et al.*, 2006; Weis *et al.*, 2006). We found that during understorey reinitiation in clear-cut and shelterwood systems nitrate leaching was higher as compared to the current climate. This was due to a retarded understorey tree development as a consequence of increasing water stress in summer and nutrient deficiency. Nitrogen was therefore taken up by trees less efficiently, transpiration was lower and higher infiltration enhanced the transport of nitrate below the rooting zone and subsequently into the groundwater. Norway spruce is a climate sensitive tree species because of its vulnerability to soil water shortage in summer (Lévesque *et al.*, 2013; Zang *et al.*, 2014). A number of studies showed, that seedlings of Norway spruce are even more sensitive to drought than mature trees. (Ditmarová *et al.*, 2010)showed that seedlings in pots indicated significant responses in a number of physiological variables after only half a month of desiccation. Also in the field it has been shown that the shallow rooting spruce seedlings were extremely sensitive to dry and hot conditions after canopy removal in (Diaci *et al.*, 2005). Apart from the soil water supply other factors influence Norway spruce regeneration. Managed mountain forests on shallow limestone soils are sensible to nutrient loss (Weis *et al.*, 2001; Christophel *et al.*, 2013). A recent study in the Northern Limestone Alps in Germany showed that nutrient loss after wind throw caused significant nutrient limitation for the regeneration (pers. comm. Kohlpaintner, Pröll). Landscape-DNDC predicted severe N-shortage for planted trees after the removal of overstorey trees. However, it has to be stressed that Landscape-DNDC is not modeling other nutrients than N such as K or P dynamics, which are at least as important as N on limestone soils (Mellert and Ewald, 2014). Hence the predicted sole growth limitation due to N is a simplification to some extent. Another limitation of our modeling approach is that we could not consider microsites. Regeneration of Norway spruce is more successful on convex microsites where a thick humus layer occurs and competition from grasses is low (Diaci *et al.*, 2005; Baier *et al.*, 2007).

5.5.3 Nitrate loss in mature stands

In our Landscape-DNDC simulations, the enhanced growth of spruce trees under the climate scenarios outweighed the stem wood biomass accumulation under the current climate and, consequently, nitrate loads to the groundwater were lower in the later period of stand development. Climate warming has been beneficiary for the growth of Norway spruce in Europe (Pretzsch *et al.*, 2014). In the Northern Limestone Alps montane and subalpine spruce forests however, a clear temperature-driven growth increase was not observed in a large tree ring analysis because of other confounding effects such as precipitation and drought(Hartl-Meier *et al.*, 2014a; Hartl-Meier *et al.*, 2014c). Nevertheless, temperature correlated positively with growth on sites > 1200 m altitude. Although the study site is at 950 m our model predicted significant future increase in growth of mature Norway spruce. This is probably to the warming scenarios of >3°C compared to only 1°C since the 1990s in the above tree ring study. Norway spruce is sensitive to drought at lower elevations (Zang *et al.*, 2014). Drought events had a negative effect to growth of *Picea abies* on sites below 1400 m in the Northern Limestone Alps for about 5 to 10 years (Hartl-Meier *et al.*, 2014c).From isotope analyses of tree rings taken at the study site we further found that though severe drought events were related with reduced growth a fast recovery took place (Hartl-Meier *et al.*, 2014b) which is rather typical for Norway spruce (Pretzsch *et al.*, 2013). This is in line with the relatively weak effect of increasing water shortage on long-term tree growth in our modeling results. But we should be cautious as to the effects of severe droughts because a change in extreme events is not well captured in our future climate scenarios (see discussion below).

5.5.4 Uncertainties

The results of the regional climate model COSMO-CLM with which our climate scenarios were derived deviate significantly from observed data (Haslinger *et al.*, 2013). Since we used only relative changes in the scenarios together with a weather generator to increase or decrease parameters of a long-term climate series, these uncertainties are less important. However, particularly precipitation exerts regional and seasonal differentiations which are probably not well addressed and should therefore interpreted with caution. Our use of the weather generator assumes that the variability in meteorological parameters does not change because we only take into account the changes in the corresponding monthly means. This has implications as to the inability to assess changes in extreme events(Wilks, 2010). More severe runoff events may increase nitrate leaching and summer droughts may be more severe in future than we assume with an even larger effect on growth reduction during the stand reinitiation. Our results may therefore reflect the weak end of possible effects in future.

Modelling whole ecosystem change owing to climate perturbation is challenging. Validation of the predictions of a complex model such as Landscape-DNDC is best done with long-term measurements of a number of sensitive parameters. We have used tree growth, soil moisture and soil solution chemistry as the main validation parameters (Kiese *et al.*, 2011). Growth was only slightly overestimated by the model but the validation period covers only 13 years, so we do not know if the modelled growth of younger trees performs equally well. Soil moisture seems to fit quite well but fluxes are much more difficult to measure and can only be compared with data from other than the used model. The same holds for nitrate fluxes. Nevertheless, the ranges of modelled values are comparable to measurements at the site and elsewhere. Additionally, we focus our interpretation on relative changes rather than absolute values. We may argue that since Landscape-DNDC captures the main processes of the nitrogen cycle and has been shown to work successfully in comparable systems the results are reliable and exemplify the main effects we might expect in future.

Indirect effects of climate change on forest ecosystems, such as wildfire, windthrow and insect outbreaks, may be more severe than direct effects(Seidl *et al.*, 2014). These disturbances not only increase nitrate leaching in forests with saturated N status(Huber, 2005) but also erosion of soil organic matter with subsequent effects on a number of forest functions. The long-lasting effects of disturbances on N cycling in forests have recently been shown in the Hubbard Brook Experimental Forest in the northeastern United States(Bernal *et al.*, 2012). These climate-driven disturbances are not included in our approach.

5.6 Figures

Figure 10. Comparison of measured and modelled soil moisture data. The observed data stems from 3 sensors in the depth of 20 cm (n=2) and 28 cm (n=1). The grey bars show the daily precipitation sums.

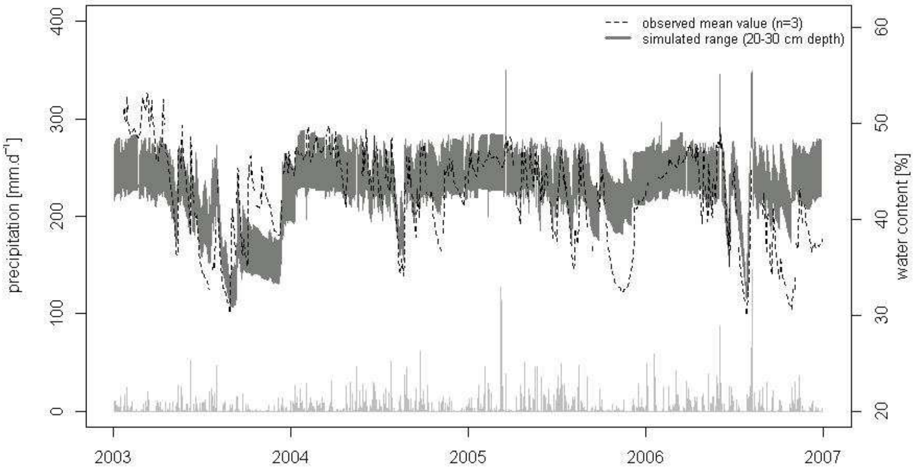


Figure 11. Comparison between measured and modelled nitrate concentration in soil seepage water. Measurements stem from concentrations in samples of 6 plate lysimeters between 2000 and 2009.

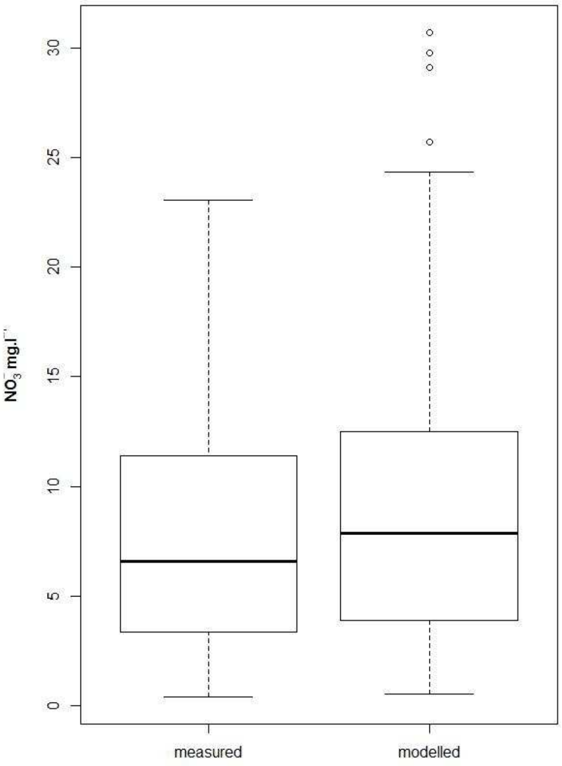


Figure 12. Cumulative nitrate leaching under climate change (A1B Emission Scenario, ECHAM5) and three different forest management practices: CFM: continuous forest cover spruce-beech management; SCM: shelterwood-cut management; CCM: clear-cut management.

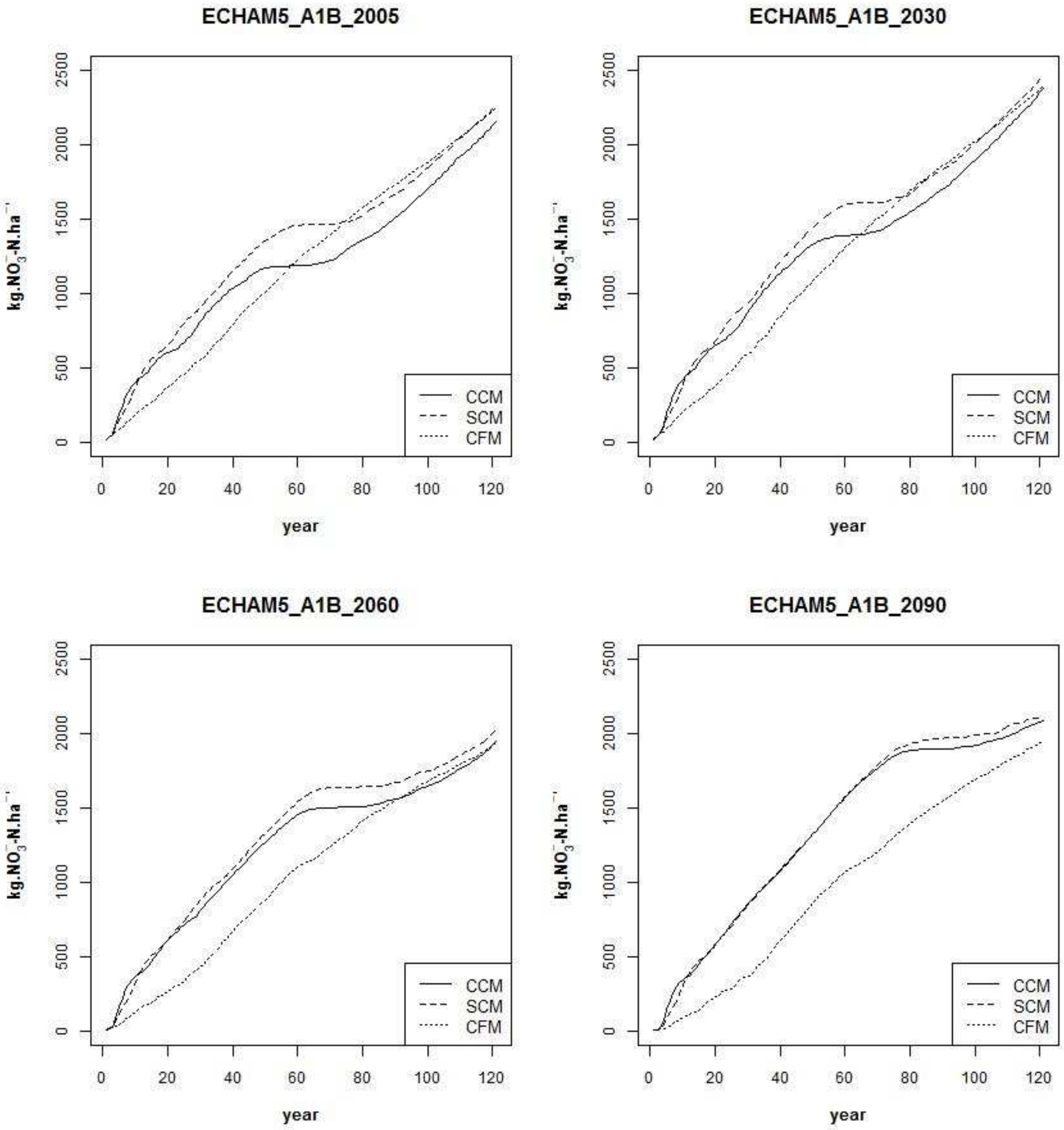
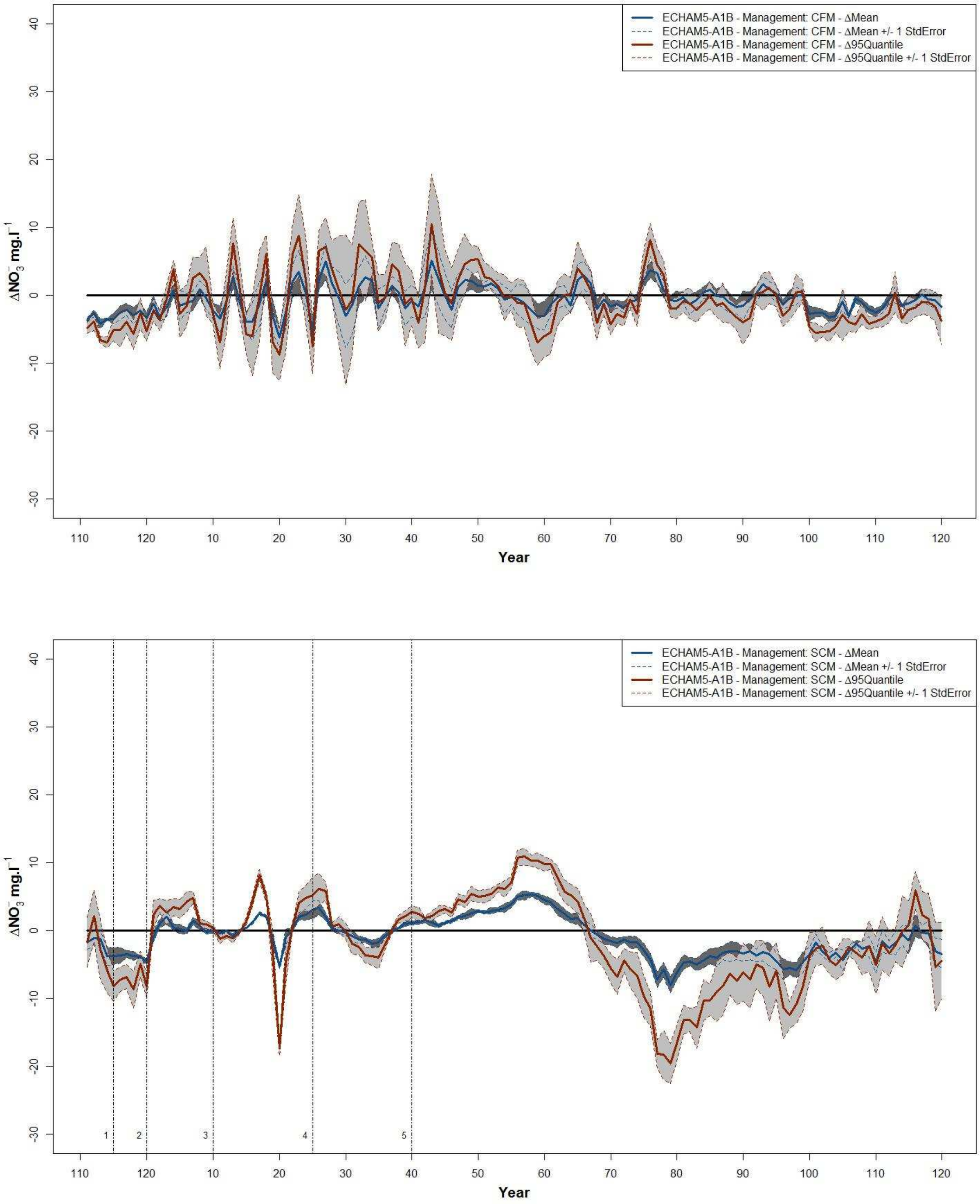


Figure 13. Climate effects to nitrate concentration in seepage water during a rotation period of 120 years. Shown is the difference between the current climate (red horizontal line) and an ECHAM5-A1B scenario by the year 2060 (blue line with interannual variation in grey shade). Upper to lower: CFM, SCM (vertical lines: 50% felling, total felling, three thinnings of new tree generation), CCM (vertical lines: 100 % clear-cut, three thinnings of new tree generation).



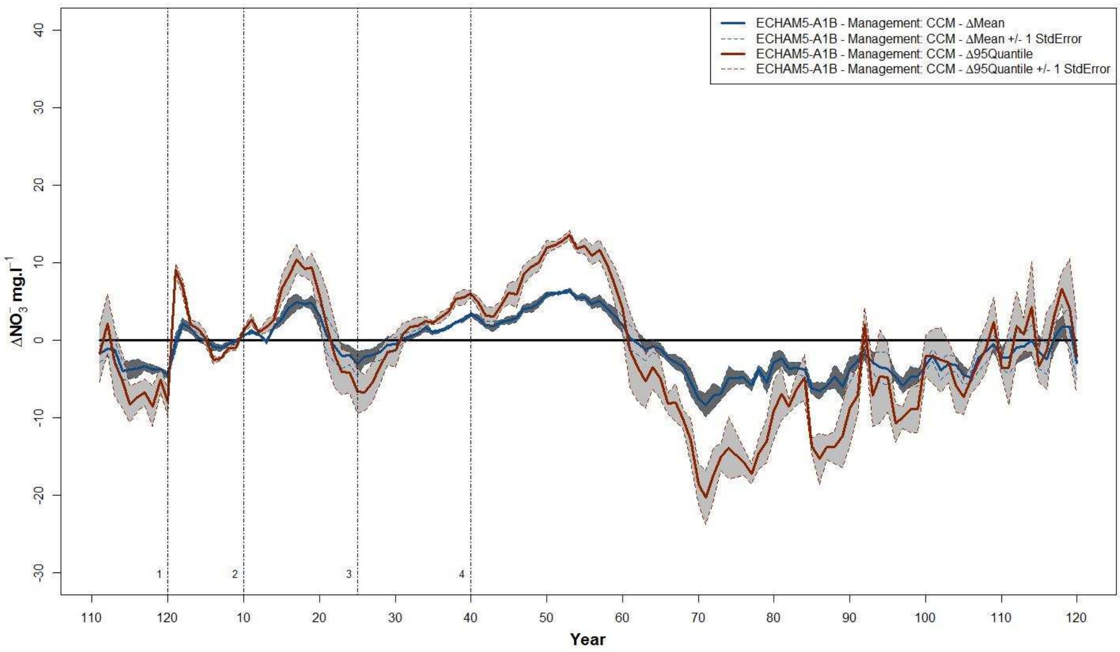
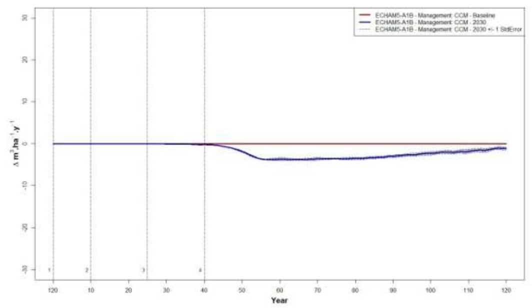
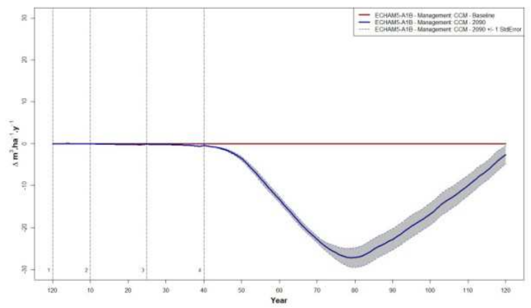

ECHAM5-A1B - Management: CCM - ΔMean
ECHAM5-A1B - Management: CCM - ΔMean +/- 1 StdError
ECHAM5-A1B - Management: CCM - Δ95Quantile
ECHAM5-A1B - Management: CCM - Δ95Quantile +/- 1 StdError
ΔNO3 mg.l-1
40
30
20
10
0
-10
-20
-30
1
2
3
4
110
120
10
20
30
40
50
60
70
80
90
100
110
120
Year

Figure 14. Climate driven change in factors controlling nitrate leaching during a rotation period of 120 years Norway spruce forest with clear cut management (vertical lines: 100 % clear-cut, three thinnings of new tree generation). In each graph we show the difference between the current climate (red horizontal line) and an ECHAM5-A1B Emission Scenario by the year 2030 and 2090 (blue line with interannual variation in grey shade).Stem growth: annual stem growth increment in m³.ha^{-1}; percolation: annual amount of seepage water in l.m²; Drought: annual mean ratio between daily water content in the rooting zone and the maximum water content.

<table>
<tr><th></th><th>2030 ECHAM5-A1B</th><th>2090 ECHAM5-A1B</th></tr>
<tr><td>Stemgrowth</td><td>
</td><td>
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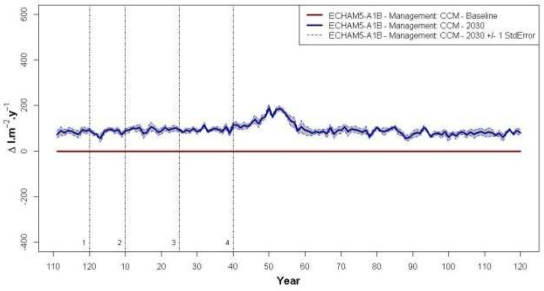
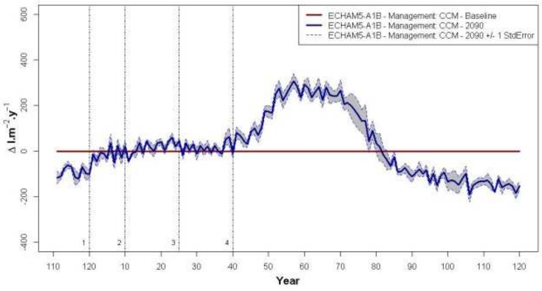
<tr><td>Percolation</td><td>
</td><td>
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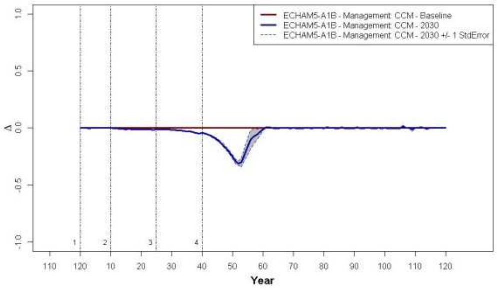
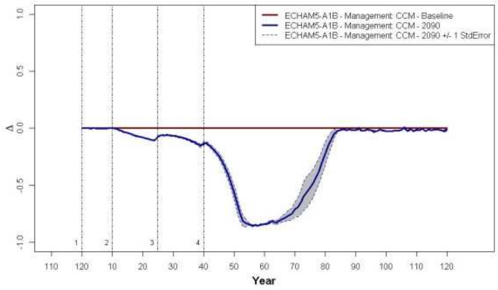
<tr><td>Drought</td><td>
</td><td>
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6. Annex 3 - Event-Monitoring and Event-Sampling

(Hermann Stadler, Joanneum Research)

This report describes the implementation of the field work. Main part of the report is according to the assignment the interpretation of gathered isotopic data combined with available high-resolution in-situ measurements. The whole field campaign was conducted in intense cooperation with the colleagues of the Austrian Environment Agency, namely Thomas Dirnböck, Johannes Kobler and Martin Kralik.

6.1 Experimental Section

6.1.1 Study area

The study is situated in the Northern Calcareous Alps in the National Park „Kalkalpen“. Altitude ranges from approximately 400 m a.s.l. to 955 m a.s.l., dominant lithology is Hauptdolomit, the core investigation area of “Zoebelboden” is characterized by flat plateaus with an altitude between 880 m a.s.l. and 950 m a.s.l. and steep surrounding creeks and torrents, leading down to altitudes at about 400 m a.s.l..

The two main investigation points are weir WM0551 at Zoebelgraben (a right side tributary to Großer Weißenbach) at an altitude of about 600 m a. s.l. and weir WM0552 at an altitude of about 520 m a.s.l., a nameless left side tributary to Großer Bach. Both measuring sites represent sub-catchments with dolomite-karst springs and a not quantifiable percentage of surface runoff and shallow interflow.

6.1.2 Measuring devices

The amount of rainfall was measured with a tipping bucket W5720 from UMS, Munich with a resolution of 0.2 mm and stored with a time increment of 15 minutes with a GEALOG-KOMPAKT from Logotronic, Vienna. At both existing measuring weirs (MW 551 and MW 552) GEALOG-S data-loggers with pressure probes (PDCR1830, Druck, London, Great Britain) and Conductivity cells (TETRACON325, WTW, Weilheim, Germany). The storing interval was 15 minutes. During the event at MW551 the increment could be reduced to 5 minutes. The automated samples were taken with BÜHLER-2000-Samplers and PB-MOS. As these devices could not be installed directly at the weirs, a hose was installed between the weirs and the automatic samplers. At MW 551 the hose was 340 m long, at MW552 at about 25 m. At MW 552 the measuring devices were installed directly at the weir and the data were digitally transmitted to the data-logger. The automated sampling was triggered by the water-level. At MW 551, the additional measuring devices were installed near the automatic samplers. The trigger criterion was derived from conductivity. For this workout only electrical conductivity of this device was used after comparing the measurement readings with the data from the instrument, which is installed continuously. Water temperature and water-level (discharge) was used from the instrument at the weir.

For this workout conductivity and discharge data collected from Umweltbundesamt at weir 551 are additionally used.

The measurements of all spectrometric parameters were done by members of Umweltbundesamt. In this workout the absorption coefficient at 254 nm (SAC254) was used. This parameter was calculated in accordance to DIN 38404-3 from the extinction at 254 nm. Missing extinction data at 550 nm, turbidity correction was not executed.

6.1.3 Communication System

The system, which was used here, enables fully automated event sampling and real-time availability of data. By means of networking via Low Earth Orbiting Satellites data from the precipitation station (PS) in the catchment area are brought together with data of the spring sampling station (SSS) without the need of terrestrial infrastructure for communication and power supply. Therefore a completely automated event sampling procedure is made possible. Furthermore the whole course of input and output parameters, like precipitation (input system) and discharge (output system) and the status of the sampling system, is transmitted via LEO-Satellites to a Central Monitoring Station (CMS) which can be linked with a web-server to have unlimited real-time data access. The automatically generated notice of event to a local service team of the sampling station is transmitted in combination with internet, GSM, GPRS or LEO-Satellites.

Within the paper the assembling, the stream of data and status information as well as the results of automated sampling in comparison with classical sampling procedures are described in detail.

Assembling: The PS is equipped with a tipping bucket, a data logger and a LEO-Satellite modem. It can be supplemented with additional meteorological sensors. The measuring and sampling site at the spring (spring sampling station, SSS) is equipped with an additional data logger, a pressure probe to register the changing of discharge, two automatic sampling units (one for the reference sample and one for the periodic samples) and a LEO-Satellite modem for real-time control and data transmission. It can be supplemented with additional hydrological or meteorological sensors.

Stream of data and information: The PS records rainfall and other meteorological data. From the intensity and the recorded amount of precipitation a specific trigger criterion is derived. If this trigger-level is exceeded, the PS activates one or more SSS via satellite (data stream 1, Figure 15) to take the reference sample. This happens before the event affects the discharge of the spring. The CMS is also informed via satellite by receiving periodic data sets from the PS to observe the further trend of precipitation (data stream 2, Figure 15).

As soon as the activation data-set is received at the SSS, the automatic sampling unit takes the reference sample. The status is sent to the CMS (data stream 3, Figure 15).This procedure can be repeated several times, depending on the number of sampling bottles in the automatic sampling device. This is necessary because due to the hydrological boundary conditions the upcoming event at the spring is worth sampling.

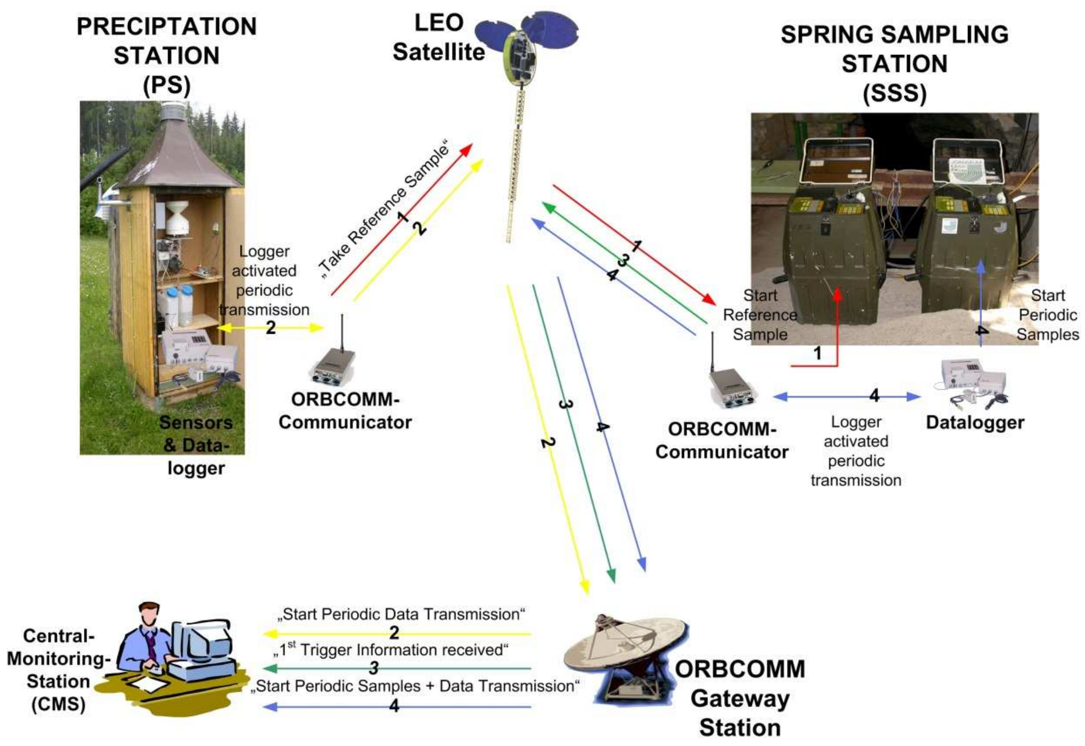


Figure 15: Block-diagram of assembling. Stream of data and information of an event-triggered LEO Satellite hydrology network

Now the SSS is waiting during a specified period of time for the increase of the discharge (or decrease of conductivity), which is the second trigger event. The trigger level is derived from the increase of the gauge height within a period of time and is chosen according to the characteristics of the spring. This trigger criterion is activated from the data logger. If the predefined trigger level is exceeded, periodic sampling is started automatically. The information is sent via satellite to the CMS. The SSS starts also periodic data transmission to the CMS to trace this event (data stream 4, Figure 15).

At the CMS the information from all stations is collected. Additionally the local service team is informed from the CMS automatically of important facts like starting of rainfall (1st trigger) and starting of the sampling procedure at the SSS (2nd trigger) via GSM cell phones. Depending on the sampling time increment and the number of bottles in the automatic samplers, they can predict their next visit at the SSS to maintain the station.

The CMS provides an online Internet-Portal for access to those environmental data. It is built around the server-based operating system Debian, which is a very stable free software, providing perfect interaction and performance with the server. Among others, the server comprises a RAID-system for fault-tolerant operation.

Despite technical problems of the Orbcomm-system (enhanced delay times) the automated event-sampling could be performed correctly. The automatic samples started at August 22, 2012, 11:17 pm at WM0551 and ended at August 30, 2012, 12:00 am at WM0552.

Reference samples were taken twice a day starting at August 20, 2012, 6:50 pm at WM0552 and August 20, 2012 7:40 pm at WM0551.

The stable environmental isotopes ^{18}O and Deuterium were analysed at the Laboratory of JOANNEUM RESEAERCH.

6.2 General overview, event characterization

6.2.1 General overview

During the investigation time three events could be monitored and samples could be taken.

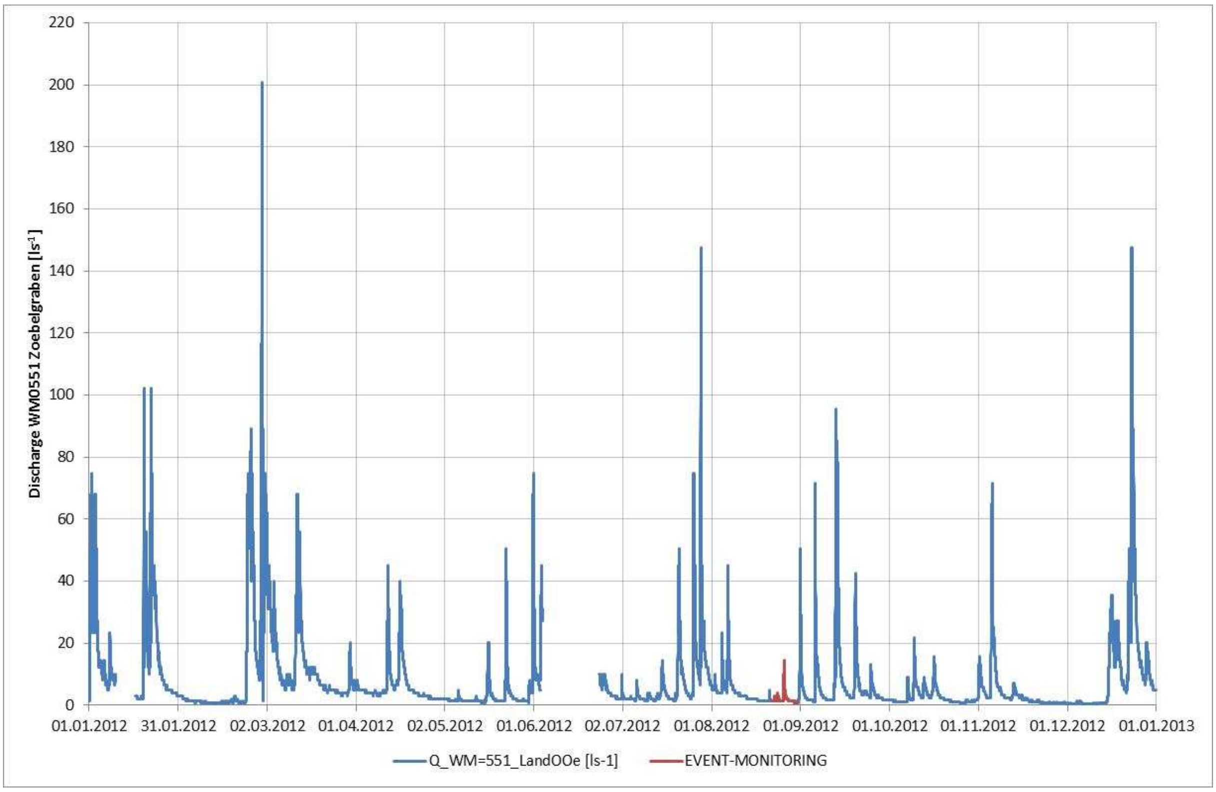


Figure 16: Runoff at WM0551 (Zoebelgraben) 2012

Due to unpredictable weather conditions, unfortunately only small runoff-events could be monitored. Looking in detail to the hydrograph in Figure 16, it can be seen that small events are not rare from spring to autumn. Although they have no long-term influence to the runoff of the sub-catchments, their contribution to storage and runoff dynamics are not negligible, they are a characteristic contribution to summer dynamics and represent therewith current climate conditions.

6.2.2 Event characterization

As seen in Figure 16, the last discharge event before our event sampling campaign happened at Aug 7, 2012, reaching a discharge of 45.1 l^{s-1} at the measuring weir 551 – Zoebelgraben. This event was caused by a precipitation of 19.4 mm within 5 hours.

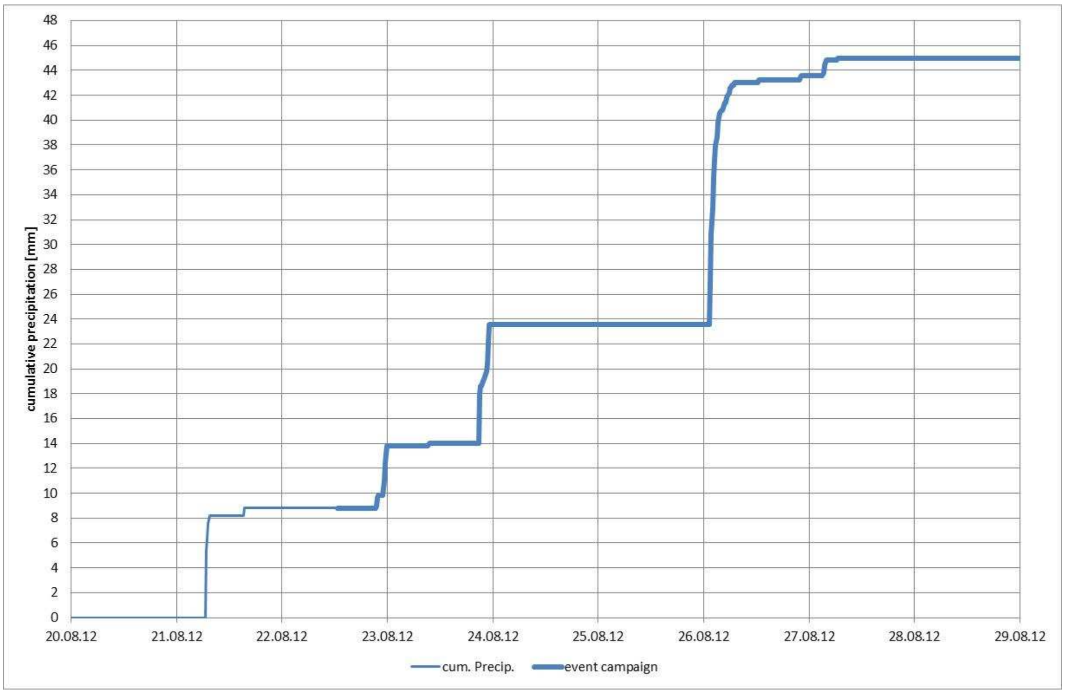


Figure 17: precipitation events during sampling campaign

The precipitation events during the campaign are shown in Figure 17. The whole amount of precipitation was thereby 36.2 mm. For the further workouts the events from August 23 to 24 and the event from August 26, 2012 are discussed.

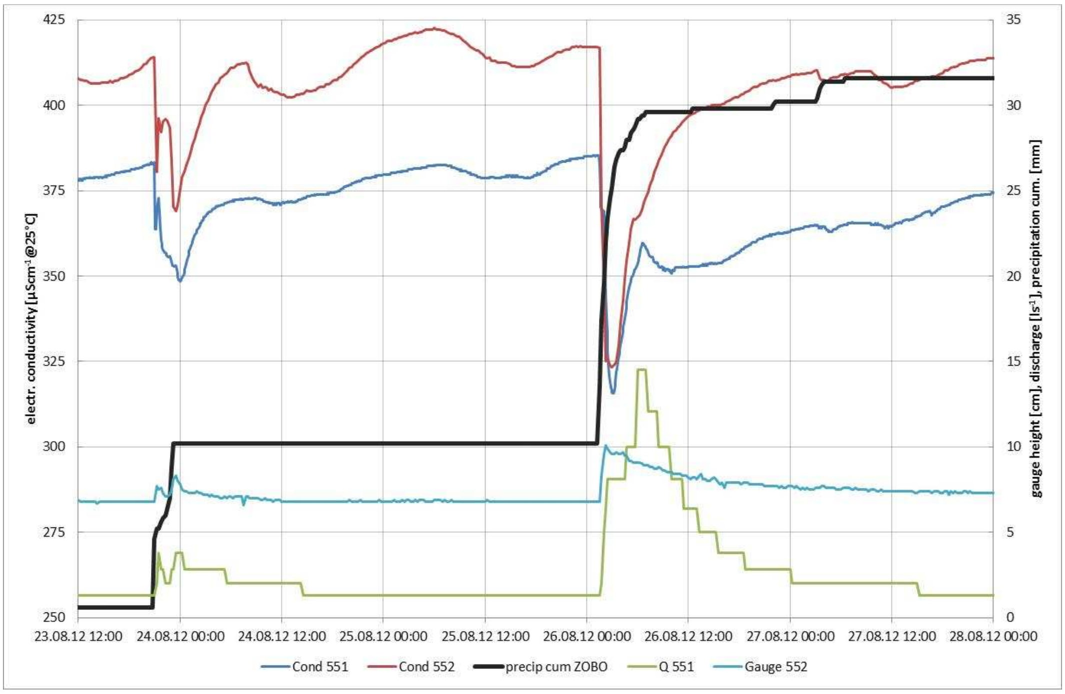


Figure 18: Discharge (gauge height), conductivity and cumulative precipitation at the measuring sites Zoebelgraben (551) und Großer Bach (552).

In Figure 18 discharge and conductivity of both measuring sites and the precipitation from the plateaus Zoebelboden (900 m a.s.l.) are shown. Looking at the discharge it can be seen, that the response to the precipitation is really straight. On August 26 the rainfall started at 01:30 a.m., the increase of discharge started at 01:45 a.m. Thereby it is to mention, that data a recorded with a 15 minutes time increment. This immediate response is attributed to surface runoff or shallow interflow at the steep slopes of the micro catchments. Karst water components in dolomitic aquifers as found in this catchment, have significant longer response times.

A second interesting fact, also supporting the above interpretation is the hydraulic response to the precipitation, especially on August 23, 2012. This precipitation event is structured in two phases, seen clearly at the course of the cumulative precipitation in Figure 18 and Figure 19. The response of discharge at both weirs is therefore separated in two peaks.

The course of conductivity show considerable dilution during the events. As shown later, this is only partly triggered by karst phenomena.

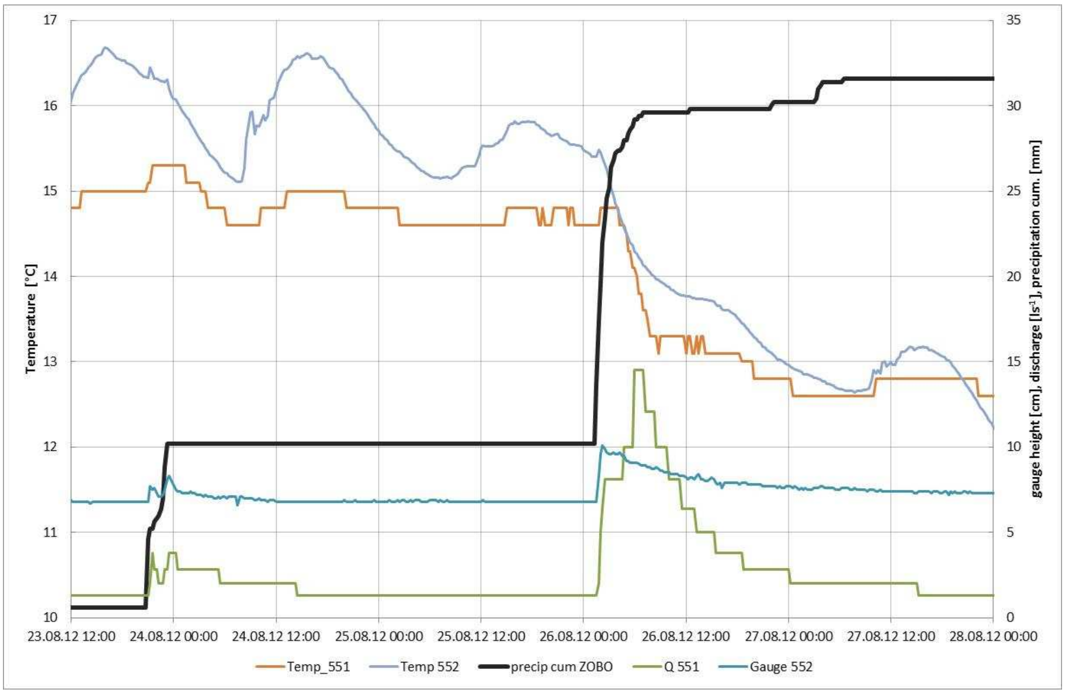
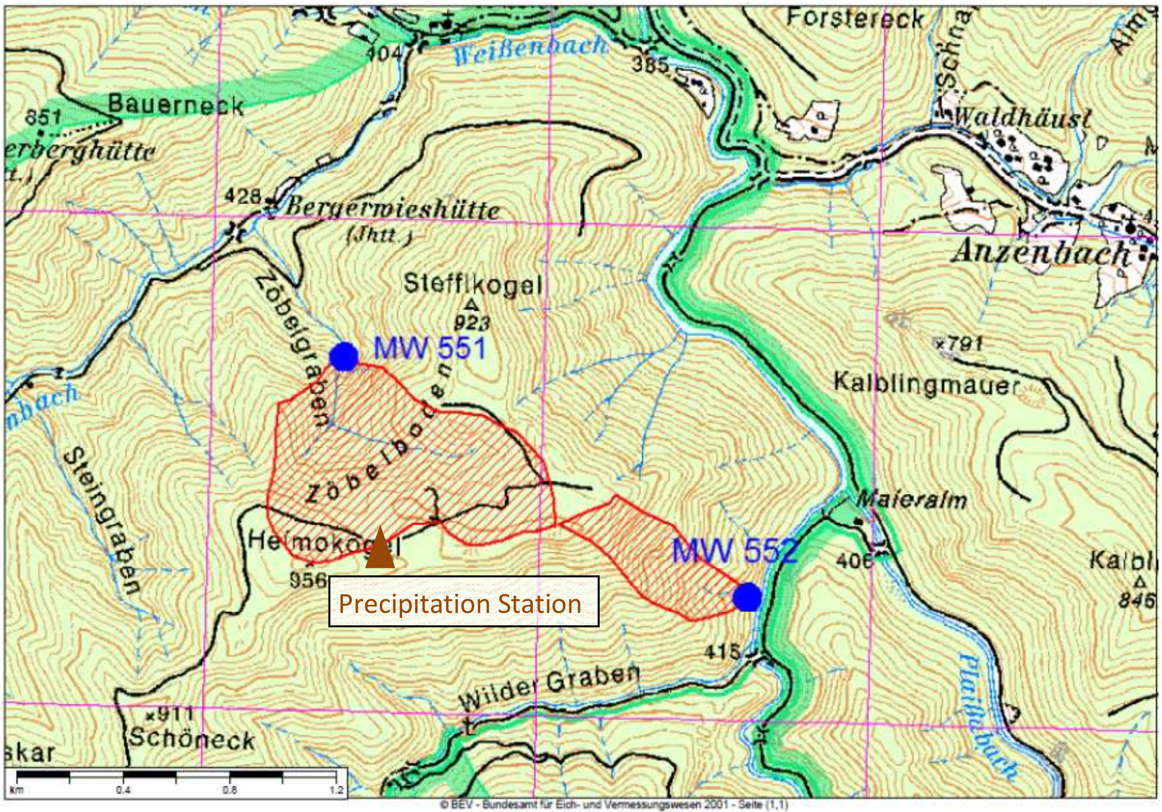


Figure 19: Discharge (gauge height), water temperature and cumulative precipitation at the measuring sites Zoebelgraben (551) und Großer Bach (552).

In Figure 19 water temperature are shown combined with discharge and precipitation. Here the above mentioned fact is confirmed by the daily amplitude of water temperature. The oscillation can be more clearly seen at site 552 as at 551. Measuring site 551 is N-exposed so the sunshine duration is shorter than at the E-exposed catchment of 552. During undisturbed conditions before the event, the runoff in the torrent is affected by sunshine and air temperature and shows therefore the characteristic oscillation with similar time delays to sunshine as air temperature.

6.2.3 Catchment areas



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Österreichische Karte 1:50 000 (OK50-Ost)

Figure 20: Measuring points and Catchment areas of automated event sampling

In Figure 20 the sample points with their orographic catchment areas and the precipitation station are located. Additional equipment was mounted, so that the existing systems are not affected. The precipitation station was erected only during event sampling campaign near the existing one. The orographic catchment area of weir 551 (Zöbelgraben) is at about 0.55 km², at weir 552 (Grosser Bach) approximately 0.14 km². So at both measuring points both spring water from dolomitic karst springs and surface runoff during event conditions can be recorded. In this terminology surface runoff includes also near surface interflow.

The whole area of Zoebelboden and the investigated catchments is dominated by “Wettersteindolomit”. Only in small areas of the plateau some overlaying “Plattenkalke” exist (GBA 1999). They do not influence the drainage system appreciable. Some amorphic debris at the plateau auf Zoebelboden is also of minor importance for the catchment behavior.

6.2.4 Sample treatment

During the automated sampling samples were stored in the sampling device not longer than 24 hours till August 26, 2012, 4:00 pm. After that time till the end of automated sampling at August 30, 2012, the samples were stored in the sampler for 4 days. After removing from the sampler samples were stored at a refrigerated warehouse in the local inn. Samples for chemical and isotopic analyses were filtered with 0.45µm. Samples for spectroscopic analyses were filtered with a 0.70µm glass filter.

6.3 Event monitoring and sampling

Main target of the event sampling was to investigate discharge and storage dynamics during event conditions by means of event sampling and event monitoring at two measuring sites. The combination of in-situ measurements of rainfall triggered events with laboratory analyses allows a deeper insight to the system and enables process orientated interpretation of hydrological data combined with biological parameters. Focal points of investigation are therefore environmental isotopes, selected chemical parameters (NO3, …) and spectroscopic analyses supplemented with DOC analyses. These laboratory analyses are combined with in-situ measurements of electrical conductivity, temperature and discharge (water level).

6.3.1 Event sampling at WM0551 – Zoebelgraben

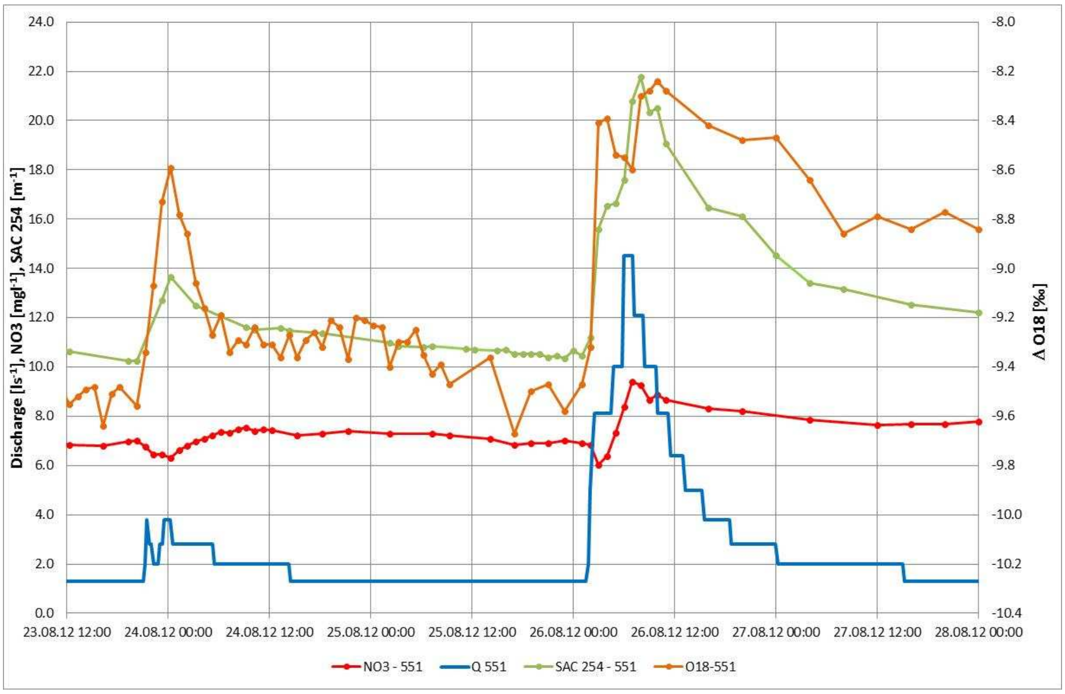

Figure 21: Event sampling at MW551. Course of discharge, nitrate, SAC254 nm and ^{18}O

At Figure 21 the most significant parameters during the monitored events are shown. The SAC254 and ^{18}O show the most significant variations. As SAC254 is known as a surface related contamination parameter (Stadler et al., 2010) the reaction to precipitation comes immediately. The later response of discharge is regarded to the resolution of the water level registration at weir 551. More details are seen at the course of ^{18}O. As part of the water itself, this environmental isotope allows direct view to water transport without disturbance by mobilization and transfer characteristics.

This clear reaction of ^{18}O is definitely triggered by the rainfall of this day. The weighted average of precipitation under spruce and beech is -7.98 δ‰ (spruce) and -8.06 δ‰ (beech). As forest stand is predominant in both catchments, these values are used as references.

The course of ^{18}O is in contrast to SAC254 more clearly separated. The first peak in the morning of August 26, 2012 is strongly correlated to the bulk of precipitation between 01:30 and 03:30 CET. The first peak at ^{18}O was reached at 3:00 CET. After that time rainfall becomes significant weaker (Figure 18 and Figure 19). The second peak of this event on August 26, 2012 shown in ^{18}O is contributed to deeper infiltration. As in the investigation area there is no karst water which has had a soil passage before, these two components cannot separated clearly with the available data. The precipitation and topsoil-water samples at different sites and specific dates show clearly damping effects (Figure 23). As the amount of precipitation was not very much (19.4 mm for the event at August 26) and the bulk of rainfall happened in a short time (17 mm within 2 hours) no higher time resolution of sampling was possible. ^{18}O shows also immediate response to precipitation. The weighted values of the event causing precipitation are -8.59 δ‰^{18}O for grassland precipitatio9n, -7.98 δ‰^{18}O for precipitation under beech and -8.06 δ‰^{18}O under spruce. These values show clear enrichment of 18O isotopes caused by evapotranspiration of precipitation from trees.

Considering the topography of the catchment, especially the great slope of the hillsides, it is possible, that reaction of the dolomitic karst aquifer is first seen by the delayed recession after August 26, 12:00 o’clock and soil passage water (which does not infiltrate to the karst aquifer) reaches the weir earlier (peak at August 26, 10:00 o’clock). In any case isotopic signature shows significant retention of water in this catchment.

The course of nitrate depicts similar processes. The comparison of the two events show major differences: The first event, caused by only 9.6 mm precipitation shows a decrease of nitrate, starting immediately after the start of precipitation. Water after the soil-passage reaches the weir after 12:00 o’clock at August 24 and causes a small recovery afterwards. The main event at August 26 (19.4 mm precipitation), shows an immediate dilution after starting of the precipitation, caused by surface flow. Corresponding

The second event caused by more or less the double amount of precipitation shows very different processes. A short dilution period (surface water) is followed by discharge of nitrate by water which has passed soil and/or karst aquifer. This process shows similar retention behavior as ^{18}O and SAC254.

6.3.2 Event sampling at WM0552 – tributary Grosser Bach

In Figure 22 the same time period and the same parameters at weir 552 (left tributary to “Großer Bach”) are seen. It is to mention, that discharge values are estimated, based on measuring of weir parameters. During the event campaign no discharge measurements could be done.

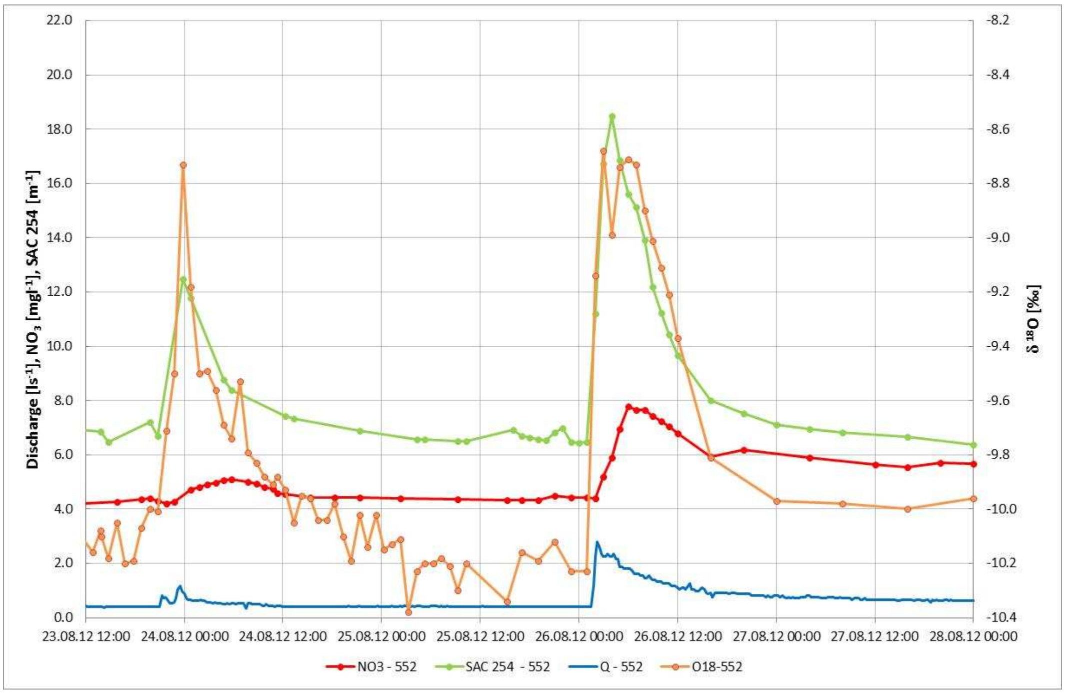

Figure 22: Event sampling at MW552. Course of discharge, nitrate, SAC254 nm and ^{18}O

The most clearly differences are shown the storage capacities in the catchment and in the nitrate discharge. The decline of SAC254 and ^{18}O after the main event (August 26), is steeper than at weir 551, showing less storage capacities. The smaller event at August 24 shows this not so clearly, because the amount of rainfall was less, causing also fewer surface runoff.

The nitrate discharge during the main event shows in contrast to 551 no effects of surface runoff dilution, also 18O shows this effect, similar to 551 but not so clearly.

6.3.3. Comparison of both measuring sites

Beside the different discharge situation, caused by the different size of the catchment, the storage dynamics of the both areas are clearly different. As lithological and geomorphological parameters are similar, the most significant difference is the absence of plateau catchment at weir 552 (Figure 21). This is a feasible reason of the differences.

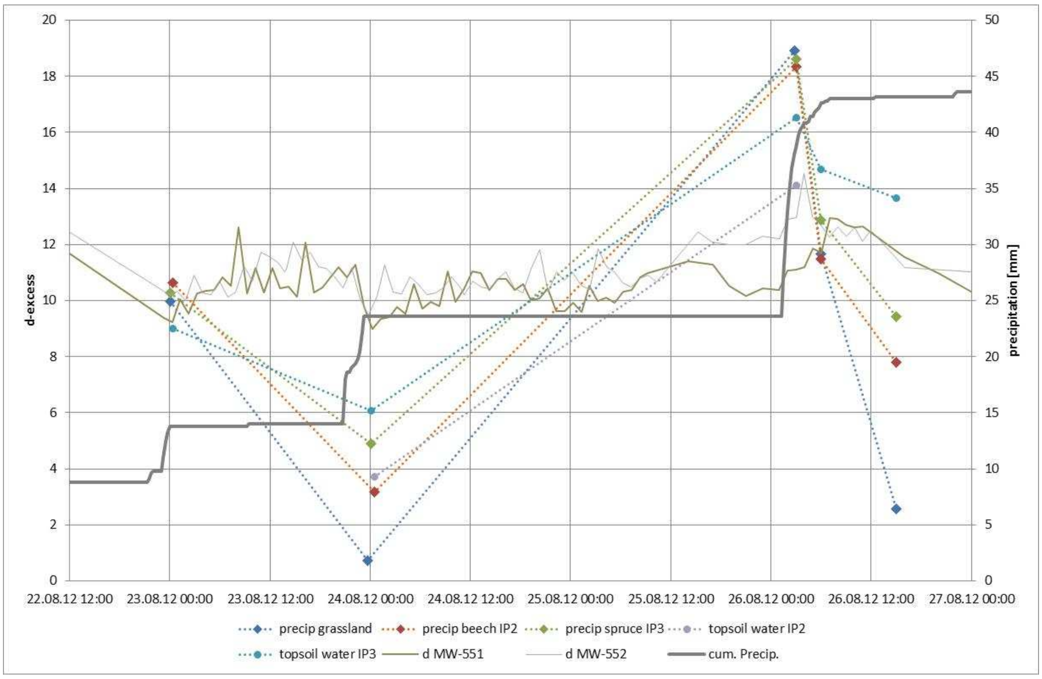

Figure 23: Precipitation and d-excess during event sampling

Figure 23 shows the d-excess of precipitation events during the observation time. It can be seen, that a great differences in the values of single events. Due to a small amount of rainfall, the events on August 23 and 24 could not be divided for sampling. During the event on August 26 three samples of different location could be taken, showing high variances. The d-excess for August 24 shows significant differences between the locations, but these differences cannot be assigned to evaporation processes directly, more samples of rainfall would be necessary.

Clearly is the reaction of the both weirs to the event. At weir 551 the reaction time is longer and the decline is slower compared to MW552, showing the better storage capacities in the catchment of MW551.

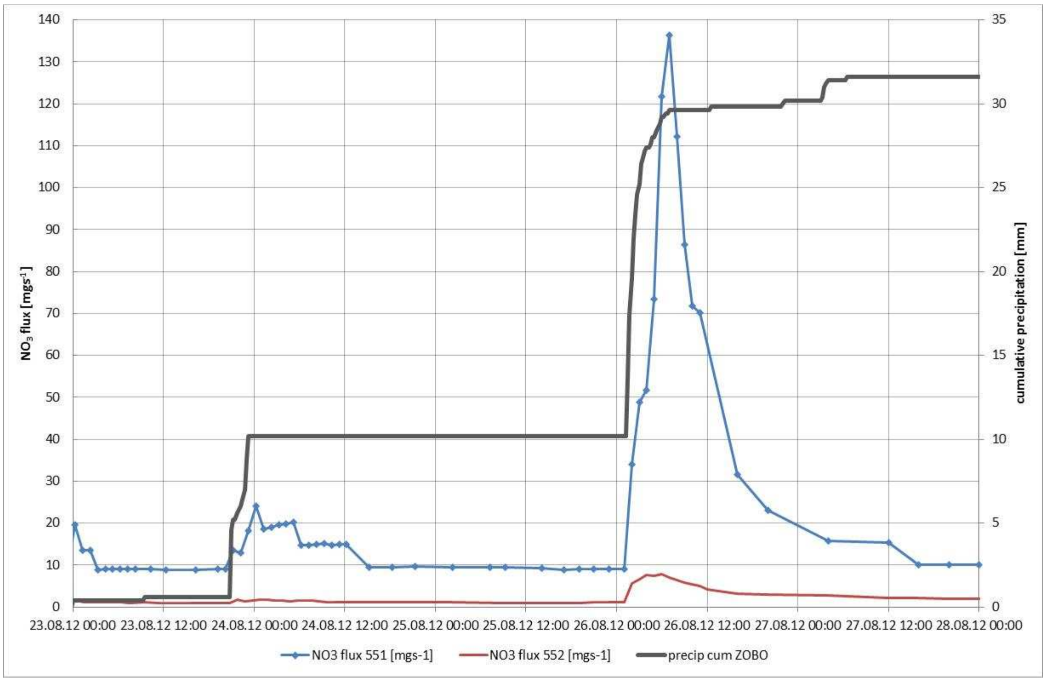

Figure 24: Nitrate fluxes at the measuring weirs during event sampling

A very significant difference is the situation of nitrate leaching. This is shown in Figure 24. A main reason of the differences is the discharge, which reaches at about 15 ls^{-1} at weir 551 and only 2.5 ls^{-1} at weir 552. The total amount of nitrate leaching during the sampling period is 11.3 kg at weir 551 and 1.3 kg at weir 552 (afflicted by some uncertainties of discharge values).

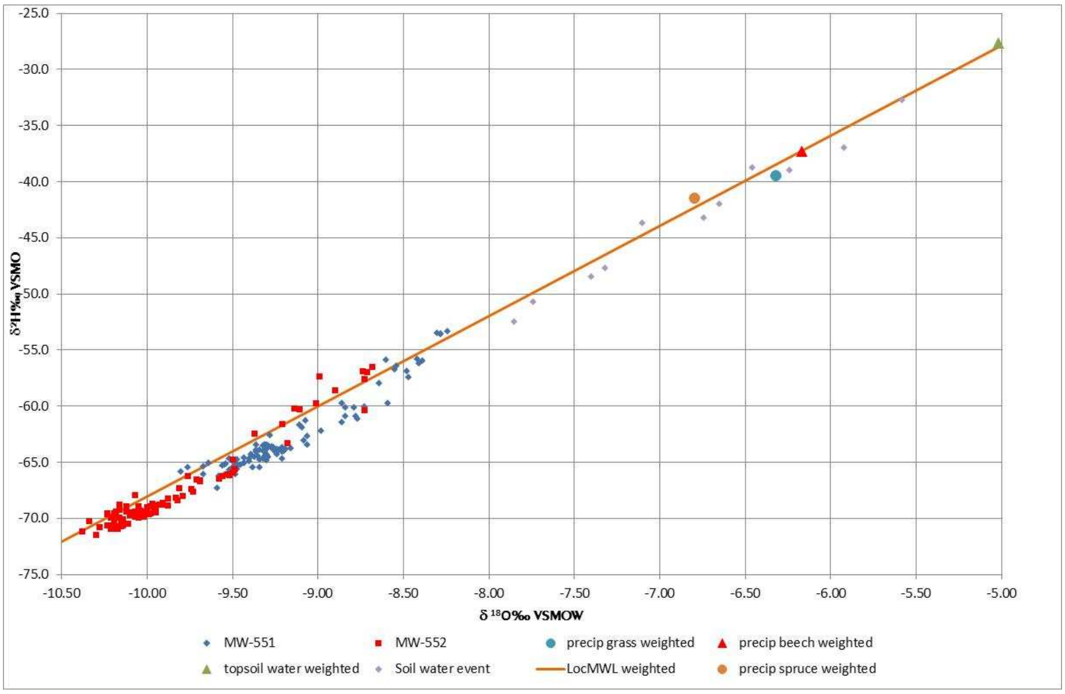

Figure 25: Local meteoric Water Line (LMWL) Zoebelboden and ^{18}O-D ratios during the event.

In Figure 25 the LMWL of the monitored event is shown. The line was calculated, using weighted values of precipitation (grassland, spruce, beech) and topsoil water under spruce (IP3). Also plotted are the values during the event sampling campaign at MW551, MW552 and of soil water under spruce and beech. (IP2 and IP3). The δ^{18}O values vary at MW551 about 1.56 δ‰, at MW552 about 1.70 δ‰, showing also less storage capacities at MW552 as shown above. These values are damped in soil water, reaching 1.11 δ‰ under beech and 1.52 δ‰ under spruce. The whole fluctuation reaches 2.27 δ‰. This could be a realistic value for catchment areas with mixed forests. At both weirs minor evaporation effects, showing the influence of surface runoff, can be seen.

6.4 Conclusions

Event sampling campaigns include always some imponderabilities caused by imprecise weather predictions. In the present case only small rainfall events could be monitored. Nevertheless such events are very typical during summer time and the direct sequence of them showed clearly different reactions at the studied catchments. The combination of data gathering with high time resolution with high frequency sampling (shortest interval 1 hour) and in-situ measurements allows process orientated interpretations.

Beside this, event-sampling and –monitoring is looking at a worst case scenario, because short-term characteristics of catchments are in the fore. Thereby process orientated event monitoring and event sampling can be a tool for estimating future climate change effect as at this scale.

The most obvious results are (1) the identification of portions of surface water at both measuring weirs and the slow reaction of the dolomitic karst aquifer and (2) and the distinct event caused nitrate leaching. This effect is characteristic for each micro-catchment and is clearly depending on the amount of rainfall.

The implication of spectroscopic parameters helped to identify surface related parameters. A future differentiation of spectral parameters will help to identify different compartments of the catchment areas.

Daily temperature effects can be explained by influence of air temperature and sunshine to the torrents, daily effects of conductivity and gauge height are apparently no technical effects of the instruments. This is seen by cross-correlation and the clear lag between the parameters. Especially as conductivity and gauge height rise with a lag of about one hour, no explanation is found in the moment. The described effect is more clearly seen at MW552.

6.5 Acknowledgements

Event sampling and event monitoring campaigns are despite of technical equipment very labor-intensive. Coordination, control measurements and sample treatment need a lot of commitment. For the sampling team hours of work does not end during rain and thunderstorm or during night. So I want to thank for the excellent cooperation with the team of the Umweltbundesamt (in alphabetical order: Thomas Dirnböck, Johannes Kobler and Martin Kralik). My special thanks go to Maria-Theresia Grabner for her patience with my questions and the provision of data. Sampling was supported by students Philipp Stadler and Stefan Rasch.

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7. Annex 4

Transit time distributions to understand the biogeochemical impacts of storm Kyrill on an Austrian karst system

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7.1 Introduction

Karst systems contribute around 50% to Austria's drinking water supply (COST, 1995). Karst develops due to the dissolvability of carbonate rock (Ford and Williams, 2007) and it results in strong heterogeneity of subsurface flow and storage characteristics (Bakalowicz, 2005). The resulting complex hydrological behavior requires adapted field investigation techniques (Goldscheider and Drew, 2007). Climate simulation indicate increasing temperature (Christensen et al., 2007) and a higher frequency of hydrological extremes(Dai, 2012; Hirabayashi et al., 2013). Both will influence the availability and quality of water provided from karst regions.

To quantify the impact of changes in climatic boundary conditions on the hydrological cycle simulation models are necessary. Special model structures have to be applied for karst regions to account for their particular hydrological behavior (Hartmann et al., 2014a). A range of models of varying complexity is available from the literature, that deal with the karstic heterogeneity, such as groundwater flow in the rock fracture matrix and dissolution conduits (Jourde et al., 2015; Kordilla et al., 2012), varying recharge areas (Hartmann et al., 2013a; Le Moine et al., 2008) or preferential recharge by cracks in the soil or fractured rock outcrops (Rimmer and Salingar, 2006; Tritz et al., 2011).

Though nitrate pollution of drinking water is usually attributed to fertilization of crops and grassland, an excess input of atmospheric nitrogen from industry, traffic and agriculture into forests has caused reasonable nitrate losses in forest areas (Erisman and de Vries, 2000; Gundersen et al., 2006; Butterbach-Bahl and Gundersen, 2011; Kiese et al., 2011). The Northern Limestone Alps area is exposed to particularly high nitrogen deposition (Rogora et al., 2006) and nitrate leaching occurs in increased rates (Jost et al., 2011).Apart from this, forest disturbances such as windthrow and insect outbreaks disrupt the nitrogen cycle and cause pronounced nitrate losses from the soils, at least in N saturated systems (Huber, 2005; Griffin et al., 2011; Bernal et al., 2012).

While many studies identify N as source of contamination in karst systems (Einsiedl et al., 2005; Jost et al., 2010; Katz et al., 2001, 2004) or provide static vulnerability maps (Andreo et al., 2008; Doerfliger et al., 1999), only very few studies use models to quantify the temporal behavior of a contamination through the systems (Butscher and Huggenberger, 2008). Some studies use N to better understand karst processes (Mahler and Garner, 2009; Pinault et al., 2001) or for advanced karst model calibration (Hartmann et al., 2013b, 2014b, n.d.) but from our knowledge there are no applications of such approaches to quantify the transient mobilization of N after strong impacts on ecosystems that mobilize a lot of organic matter.

In this study, we consider the time period of and after storm Kyrill that hit Middle Europe in early 2007 at a dolomite karst system in Austria. Kyrill and some similarly strong storms that followed 2008 caused strong damage to its ecosystem. We will apply a new type of semi-distributed model that considers the spatial heterogeneity of the karst system by distribution functions to compare the hydrological and hydrochemical behavior (DOC, N, SO4) of the system before and after the storms and to learn how N input to the hydrological system changed by the impact of the storms. Furthermore, to assess the vulnerability to such impacts, we will use the semi-distributed structure of the model to create transit time distributions that express how the impact of the storms propagated through the variable dynamic flow paths of the karst system.

7.2 Study site

The study site LTER Zöbelboden is located in the northern part of the national park Kalkalpen. Its altitude ranges from 550 m to 956 m ASL. Mean monthly temperature varies from -1 °C in January to 15.5 °C in August. The average temperature is 7.2 °C (at 900 m ASL). Annual precipitation ranges from 1,500 to 1,800 mm and snow accumulates commonly between October and May with an average duration of about 4 months. The mean N deposition in bulk precipitation between 1993 and 2006 was 18.7 kg N.ha-1.yr-1, out of which 15.3 kg N was inorganic (approximately half as NO3--N and half as NH4+-N) (Jost et al., 2011). Due to the dominating dolomite, the catchment is not as heavily karstified as limes-tone karst systems, but shows typical karst features such as conduits and sink holes (Jost et al., 2010).

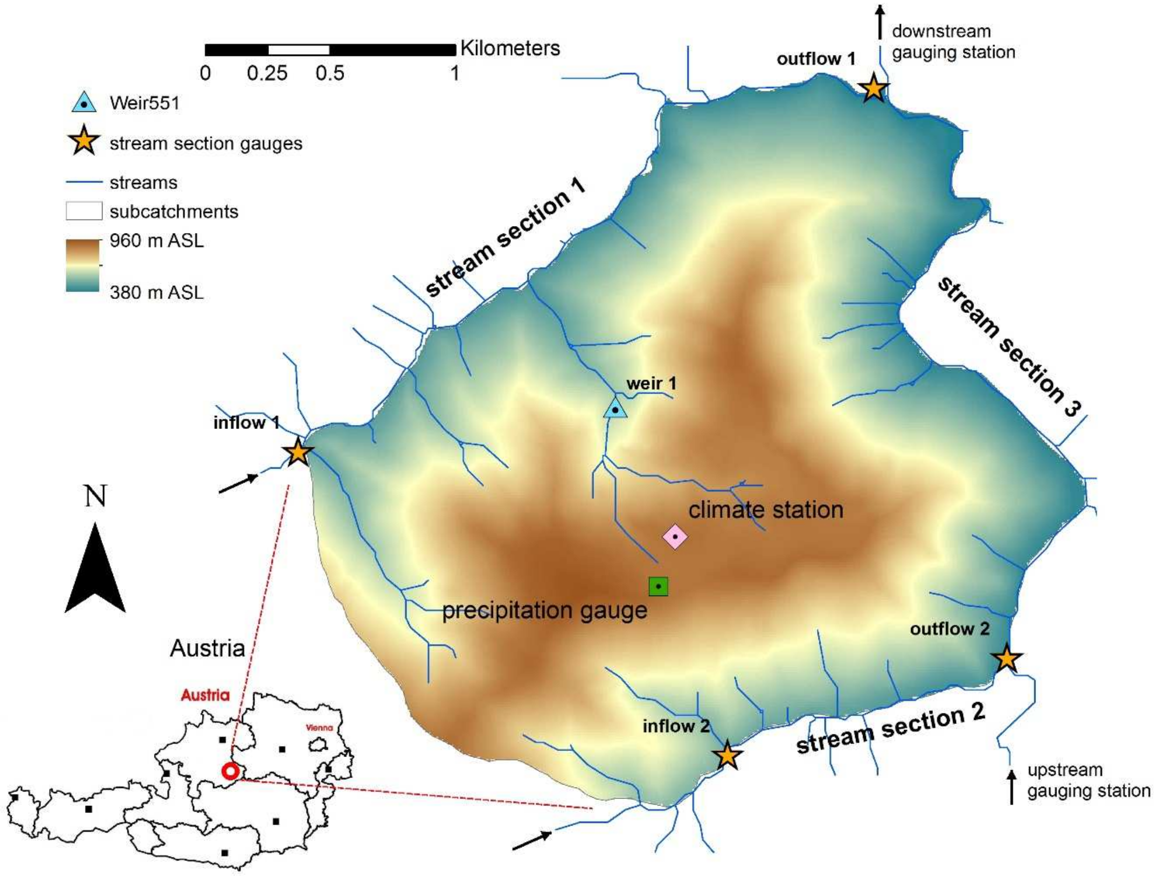

Figure 26: study site and location of measurement devices (Hartmann et al., 2012a;modified).

The site can be split into steep slopes (30-70°, 550-850 m ASL) and a plateau (850-950 m ASL). Chromic cambisols and hydromporphic stagnosols with an average thickness of 50 cm and lithic and rendzic leptosols with an average thickness of 12 cm can be found at the plateau and the slopes, respectively (WRB, 2006).

Kyrill in the year 2007 and some similarly strong storms that followed 2008 caused some major windthrows as well as single tree damages. A windthrow of ~ 5 ha occurred upstream of weir 1. Though no direct measurements exist as to the total extent of the windthrow area we estimate that 5-10 % of the study site has been subject to windthrow. Nitrate concentration in samples at weir 1 remained below ~10 mg/l since 1992 and did not exceed 15 mg/l after wind throw (unpublished data).

7.3 Methods

7.3.1 The model

Model hydrodynamics

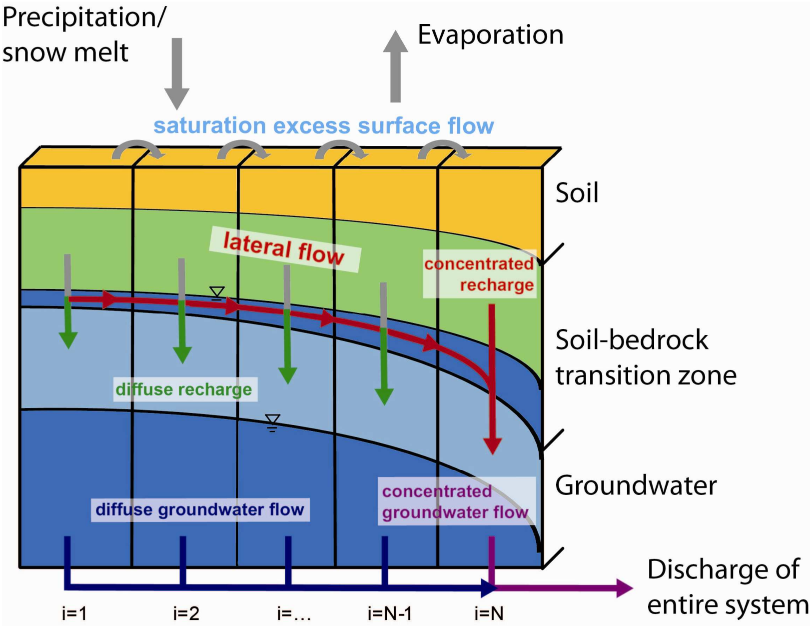

Figure 27: Sketch of model structure; it is assumed that discharge and hydrochemistry at the two weirs is composed by different mixtures of diffuse recharge (green), concentrated recharge (red), diffuse groundwater flow (blue) and concentrated groundwater flow (purple)

The semi-distributed simulation model considers the variability of karst system properties by statistical distribution functions spread over *N*=15 model compartments (Figure 27). That way it simulates a range of variably dynamic pathways through the karst system.The variability of soil depths is expressed by a mean soil depth $V_{mean,S}$ [mm] and a distribution coefficient a_{SE} [-]. The soil storage capacity $V_{S,i}$ [mm] for every compartment *i* is calculated by:

$$V_{S,i} = V_{\max,S} \cdot \left(\frac{i}{N}\right)^{a_{SE}} \tag{1}$$

Where the maximum soil storage capacity $V_{max,S}$ [mm] is derived from $V_{mean,S}$as described in Hartmann et al.(2013c). The same distribution coefficient $a_{SE}$is used to define the epikarst storage distribution by the mean epikarst depth $V_{mean,E}$ [mm] (derivation of $V_{max,E}$identical to $V_{mean,S}$):

$$V_{E,i} = V_{\max,E} \cdot \left(\frac{i}{N}\right)^{a_{SE}} \tag{2}$$

Actual evapotranspirationfrom each soil compartment at time step $tE_{act,i}$ is found by:

$$E_{act,i}(t) = E_{pot}(t) \cdot \frac{\min\left[V_{Soil,i}(t) + P(t) + Q_{Surface,i}(t), V_{S,i}\right]}{V_{S,i}} \tag{3}$$

where $Q_{surface,i}$ [mm/d] is the surface inflow originating from compartment *i*-1 (see Eq. (7)), E_{pot} [mm/d] the potential evaporation, and P [mm/d] the precipitation at time t. E_{pot} is calculated by the Penman-Wendling approach(DVWK, 1996; Wendling et al., 1991)(Wendling et al., 1991;DVWK, 1996). To account for the solid fraction of precipitation a snowmeltroutinewas set on top of the model. We used the same routine that was applied on 148 other catchments in Austria byParajka et al. (2007) and explained in Hartmann et al. (2012). Recharge to the epikarst$R_{Epi,i}$ [mm/d] is defined as:

$$R_{Epi,i}(t) = \max\left[V_{Soil,i}(t) + P(t) + Q_{Surface,i}(t) - E_{act,i}(t) - V_{S,i},\ 0\right] \tag{4}$$

Where the storage coefficients $K_{E,i}$ [d] control the outflow of the epikarst:

$$Q_{Epi,i}(t) = \frac{\min\left[V_{Epi,i}(t) + R_{Epi,i}(t) + Q_{Surface,i}(t), V_{E,i}\right]}{K_{E,i}} \cdot \Delta t \tag{5}$$

$$K_{E,i} = K_{\max,E} \cdot \left(\frac{N - i + 1}{N}\right)^{a_{SE}} \tag{6}$$

$K_{max,E}$ is derived by a mean epikarst storage coefficient $K_{mean,E}$(see Hartmann et al., 2013c).Excess water from the soil and epikarst thatproduces surface flow to the next model compartment $Q_{Surf,i+1}$ [mm/d] is calculated by:

$$Q_{Surf,i+1}(t) = \max\left[V_{Epi,i}(t) + R_{Epi,i}(t) - V_{E,i},\ 0\right] \tag{7}$$

The lower outflow of eachepikarst compartment is separated into diffuse ($R_{diff,i}$ [mm/d]) and concentrated groundwater recharge ($R_{conc,i}$ [mm/d]) by the recharge separation factor $f_{C,i}$ [-]:

$$R_{conc,i}(t) = f_{C,i} \cdot Q_{Epi,i}(t) \tag{8}$$

$$R_{diff,i}(t) = \left(1 - f_{C,i}\right) \cdot Q_{Epi,i}(t) \tag{9}$$

The distribution of $f_{C,i}$ among the different compartments is defined by the distribution coefficienta_{fsep}:

$$f_{C,i} = \left(\frac{i}{N}\right)^{a_{fsep}} \tag{10}$$

Diffuse recharge reaches the groundwater compartment below, while concentrated recharge is routed to the conduit system (compartment $i = N$). The variable contributions of the groundwater compartments that represent diffuse flow through the matrix (1…N – 1) are given by

$$Q_{GW,i}(t) = \frac{V_{GW,i}(t) + R_{diff,i}(t)}{K_{GW,i}} \tag{11}$$

$K_{GW,i}$ is calculated by:

$$K_{GW,i} = K_C \cdot \left(\frac{N - i + 1}{N} \right)^{-a_{GW}} \tag{12}$$

where K_C is the conduit storage coefficient. The groundwater contribution of the conduit system originates from compartment N:

$$Q_{GW,N}(t) = \frac{\min\left[V_{GW,N}(t) + \sum_{i=1}^{N} R_{conc,i}(t), V_{crit,OF} \right]}{K_C} \tag{13}$$

Knowing the recharge area A_{max} [km²] and rescaling the dimensions [l s^{-1}], the discharge of the entire system Q [l s^{-1}] is calculated by:

$$Q(t) = \frac{A_{\max}}{N} \cdot \sum_{i=1}^{N} Q_{GW,i}(t) \tag{14}$$

Preceding studies showed that weir 1 (Figure 26) receives its discharge partially from the epikarst and partially from the groundwater, reaching it partially as concentrated and partially as diffuse flow (Hartmann et al., 2012a). Consequently we derive its discharge Q_{551} [l/s] by

$$\begin{aligned} Q_{551}(t) = {} & f_{Epi} \cdot \left[f_{Epi,conc} \cdot \sum_{i}^{N} R_{conc,i}(t) + (1 - f_{Epi,conc}) \cdot \sum_{i}^{N} R_{diff,i}(t) \right] + \\ & (1 - f_{Epi}) \cdot \left[f_{GW,conc} \cdot Q_{GW,N}(t) + (1 - f_{GW,conc}) \cdot \sum_{i}^{N-1} Q_{GW,i}(t) \right] \end{aligned} \tag{15}$$

Where f_{Epi} is the fraction from the epikarst and $(1-f_{Epi})$ the fraction from the groundwater. $f_{Epi,conc}$ and $f_{GW,conc}$ represent the concentrated flow fractions of the epikarst and groundwater contributions, respectively. Table 5 lists all model parameters including a short description.

Model solute transport

To model the non-conservative transport of DOC, NO_3^- and SO_4^+, we equipped the model with solute transport routines. The inclusion of these 3 solutes will allow for a more reliable estimation of model parameters (Hartmann et al., 2012b, 2013a) and, further on, the evaluation of possible changes in the dynamic of solute concentrations during the stormy period. For most of the model compartments they simply followed the assumption of complete mixing. But to represent dissolution and mobilisation of DOC and N in the soil, and dissolution of SO_4 in the rock matrix, additional processes were included in the model structure. Similar to preceding studies (Hartmann et al., 2013a, 2014b) SO_4 dissolution is $Geo_{SO4,i}$ [mg/l] for compartment i calculated by:

$$Geo_{SO4,i} = Geo_{\max,SO4} \cdot \left(\frac{N - i + 1}{N} \right)^{a_{Geo}} \tag{16}$$

where a_{Geo}[-] is another variability constant and $Geo_{max,SO4}$[mg/l] is the equilibrium concentration of SO_4 in the matrix. Similar to other studies DOC availability increases with soil thickness and water table (e.g., Birkel et al., 2014; Weiler and McDonnell, 2006). Since the loamy soils at the study area, can be expected to retain the water until saturation, no consideration of water table depth was necessary. The soil only provides water to the epikarst when it is saturated (Eq. 4) and its DOC concentration $Org_{DOC,i}$[mg/l] for each model compartment is found by:

$$Org_{DOC,i} = Org_{\min,DOC} \cdot \left(\frac{N-i+1}{N} \right)^{-\frac{1}{a_{DOC}}} \tag{17}$$

where a_{DOC}[-] is the DOC variability constant and $Org_{min,SO4}$[mg/l] is the equilibrium concentration of DOC at soil compartment *i*. Similar to other studies that assessed N input to a karst system (Pinault et al., 2001) we use a trigonometric series ta asses the time variant contribution of N, $Org_{N,i}$ [mg/l], to the soil:

$$Org_{N,i} = Org_{mean,N} + Amp_N \cdot \sin\left(\frac{365.25}{2\pi} \cdot \left(JD + PhS_N \right) \right) \tag{18}$$

Here, $Org_{mean,N}$ is the mean N production in the soil, while Amp_N [mg/l] and PhS_N[d] are the amplitude of the seasonal signal and the phase shift of seasonal N uptake and release cycle, respectively. JD is the Julian day of each calendar year. Eqs. (17) and (18) are the result of a trial-and-error procedure, during which we also allowed for seasonality in DOC and variability of N uptake and release among the N model compartments. But since these additional features did not improve the simulations we discarded them for the sake of simplicity.

7.3.2 Available data

A 10 year record of input and output observations is available. Starting from the hydrological year 2002/03 it envelops well the stormy period that begins in January 2007. It includes daily rainfall measurements and stream discharge measurements from stream section 1 and 2 (Figure 26). We obtained the discharge of the entire system with a simple topography based up-scaling procedure that is described in more detail in (Hartmann et al., 2012a). Irregular (weekly to monthly) observations of DOC, N and SO_4 concentrations are available for the precipitation and weir 1. Additionally, irregular observations of snow water equivalent at the plateau allowed for independent setup of the snow routines.

7.3.3 Model calibration and evaluation

With 14 model parameter for that control the hydrodynamics and 7 parameters that allow for the non-conservative solute transport, the calibration of the model is a high-dimensional problem For that reason we chose the Shuffled Complex Evolution Metropolis algorithm SCEM (Vrugt et al., 2003) that prove itself to be capable of exploring high dimensional optimization problems (Fenicia et al., 2013; Feyen et al., 2007; Vrugt et al., 2006). As performance measure we chose the Kling-Gupta efficiency KGE(Gupta et al., 2009). For calibration, KGE is weighted equally among all solutes, 1/3 for the discharge of the entire system, and 2/3 for the discharge of weir 1 whose observations precision is regarded to be more reliable than the up-scaled discharge. KGE is defined as:

$$KGE = 1 - \sqrt{(r-1)^2 + (\alpha - 1)^2 + (\beta - 1)^2} \quad (19)$$

$$\text{with } \alpha = \frac{\sigma_S}{\sigma_O} \text{ and } \beta = \frac{\mu_S}{\mu_O} \quad (20)$$

where *r* is the linear correlation coefficient between simulations and observations, μ_S/μ_O and σ_S/σ_O are the means and standard deviations of simulations and observations, respectively α expresses the variability and β the bias.

Since SCEM also provide the posterior distributions of the calibrated parameters we can check for their identifiability to avoid over-parameterization (Perrin et al., 2003a). A parameter with a posterior distribution that deviates significantly from a uniform distribution can be regarded identifiable. Furthermore, we perform a split-sample test (Klemeš, 1986) to check the predictive skills of the calibrated model. Since the pre-storm time series was too short to be split into two equally long periods, we perform a bootstrapping to obtain two independent 4-year time series of observations (1st sample: discrete sampling of 50% of the values of each observed time series, 2nd sample: remaining observations). For a two-sided evaluation we calibrate the model with one of the bootstrap samples and apply it to the sample that was not used for calibration for validation. A parameter set is regarded as stable, when the KGE concerning discharge and the solutes does not reduce significantly.

7.3.4 Change of hydrochemical behaviour with the stormy period

Having strong indication that the model works reasonable under pre-storm conditions by the parameter identifiability analysis and the both sided split-sample test, we can use the different components of the KGE in Eqs. (20) and 20) to explore the impacts of the storm period on the hydrochemical components. We will assess the duration of the impact and compensate for apparent deviations by adapting the hydrochemical parameters in Eqs. (16)-(18). Assuming that the model is able to predict to hydrochemical behaviour that prevailed without the impact of the storms the difference between the adapted hydrochemical simulations and the non-adapted simulations will allow us to quantify the change of solute mass balance due to the storm impact. Additionally, the necessary change of parameters may indicate changes of the seasonality or inter-annual variations of the solutes.

7.3.5 Transit time distributions

The variability of storage capacities, hydraulic conductivities and flow paths the signal of the storm impact will travel by various velocities through the karst system. While fast flow paths and small storages will transport the signal rapidly to the system outlet, slow pathways and large storages will delay and dilute the signal. Distributions of transit times of water and hence other water quality parameters indicate how fast surface impacts travel through the hydrological system. We derive transit time distributions from the model by performing a virtual tracer experiment with continuous injection over the entire catchment at the beginning of the impact of the stormy period. When a model compartment reaches 50% of the tracer concentration is considered as median transit time. The hereby derived transit times will hence elaborate how the hydrological system propagates the signal through the system. In combination with the fluxes that are provided from each of the model compartments, it is possible to quantify the fractional contribution of fast and slow flow paths, respectively. We will apply the virtual tracer from the previously assessed beginning of the impact until the end of the time series to assess the transit time distribution. In addition, we apply a second virtual tracer that also starts with the assessed beginning of the impact but ends at the assessed end of the impact to evaluate the filter and retardation potential of the karst system.

7.4 Results

7.4.1 Model performance

Table 5 shows the calibrated parameters. They indicate a thick soil and a relatively thin epikarst. The dynamics expressed by the storage constants indicate are within days and weeks for the conduits (model compartment *i*=*N*) and the epikarst, respectively. The distribution coefficient of the groundwater is larger than the soil/epikarst storage constant. For DOC there is a natural equilibrium concentration of ~0.4 mg/l, which is close to 1 mg/l for N. The DOC distribution coefficient is significantly <1. The phase shift and amplitude for N show that there is a seasonal variation of N uptake and release with its maximum release at April each year. Similar to the DOC the SO4 variability constant is quite low. Weighted KGEs, as well as their values for the individual simulation variables indicate an adequate model performance and an acceptable stability for their validation data sets.

Table 5: model parameters, description, ranges and calibrated values with *KGE* performances for the calibration and validation period (1st and 2nd bootstrap sample)

Parameter	Description	Unit	Ranges		Calibrated values
			Lower	Upper	
A_{tot}	Recharge area entire karst system	km²	5.7	5.8	5.72
$V_{mean,S}$	Mean soil storage capacity	mm	0	500	493.8
$f_{Var,S}$	Mean soil storage capacity	mm	0	1	0.00
$V_{mean,E}$	Mean epikarst storage capacity	mm	0	1000	391.7
$f_{Var,E}$	Mean epikarst storage capacity	mm	0	1	0.64
a_{SE}	Soil/epikarst depth variability constant	-	0	10	5.2
$K_{mean,E}$	Epikarst mean storage constant	d	1	50	19.6
a_{fsep}	Recharge separation variability constant	-	0	10	1.3
K_C	Conduit storage constant	d	1	10	1.1
a_{GW}	Groundwater variability constant	-	0	10	8.7
A_W	Recharge area weir 551	km²	0.5	1.5	0.58
f_{EW}	Fraction of weir discharge originating from the epikarst	-	0	1	0.58
$f_{WE,conc}$	Fraction of weir discharge originating from the epikarst as concentrated flow	-	0	1	0.55
$f_{WGW,conc}$	fraction of weir discharge originating from the groundwater as concentrated flow	-	0	1	0.06

$Org_{min,DOC}$	average DOC production in the soil	mg l^{-1}	0	15	0.39
a_{DOC}	DOC variability constant	-	0.5	10	0.53
$Org_{mean,NO3}$	average NO3 production in the soil	mg l^{-1}	-5	10	0.97
PhS_{NO3}	Phase of annual NO3 production	d	0	365.25	341
Amp_{NO3}	Amplitude of annual NO3 production	mg l^{-1}	0	10	0.45
$Geo_{max,SO4}$	Equilibrium concentration of SO_4 in matrix	mg l^{-1}	0	50	2.27
a_{Geo}	Equilibrium concentration variability constant	-	0	10	0.4
$KGE_{weighted}$	weighted multi-objective model performance	-	0	1	0.50/0.49
$KGE_{Q,tot}$	model performance for discharge of entire system	-	0	1	0.37/0.38
$KGE_{Q,W}$	model performance for discharge of weir	-	0	1	0.59/0.54
KGE_{DOC}	model performance for DOC concentrations	-	0	1	0.39/0.38
KGE_{NO3}	model performance for NO_3 concentrations	-	0	1	0.35/0.54
KGE_{SO4}	model performance for SO_4 concentrations	-	0	1	0.72/0.64

* calibration/validation with other sample

The discharge simulations follow adequately the variations of the observations (Figure 28), although some small events are not reproduced by the model and although the simulations of the weir's discharge tend to under-estimate the peak flows. No obvious differences can be seen between the pre-storm and the stormy. The hydrochemical simulations tend to follow the observations, as well (Figure 29). But there is sometimes some under-estimation of the DOC peaks for the pre-storm periodas well as for the stormy period. The N simulations appear to be more precise during the pre-storm period but there is a systematic under-estimation during the stormy period. There is no big difference between SO_4 simulations and observations during per-storm and stormy period. But a slight trend from under-estimation at the beginning of the pre-storm period to a slight over-estimation during at the end of the time series is visible.

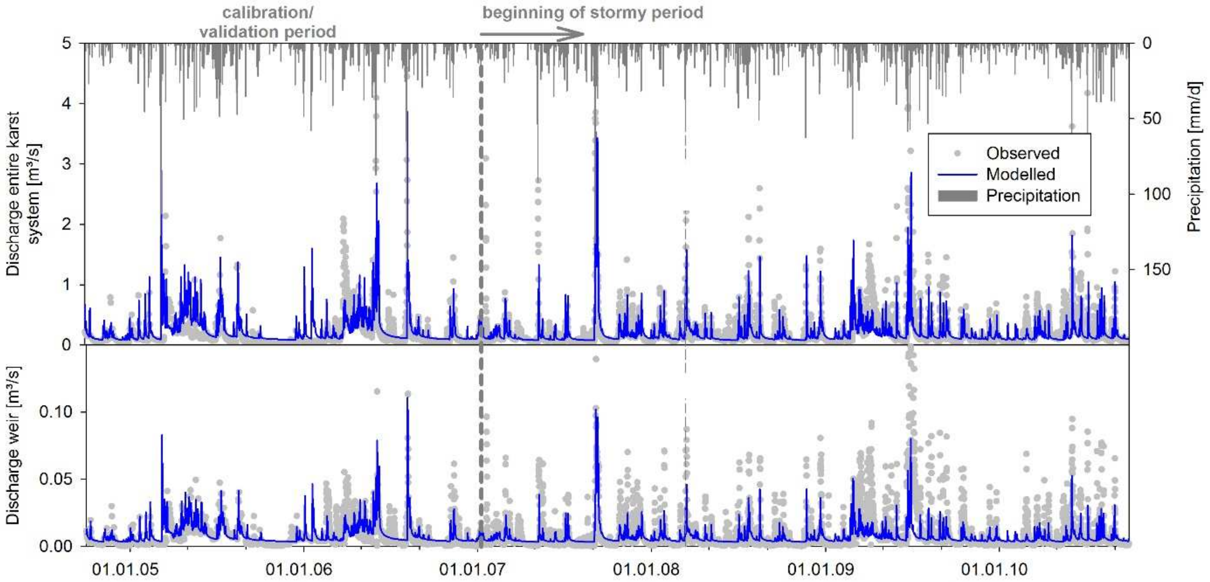

Figure 28: Observed versus simulated discharges for the entire karst system and weir 1

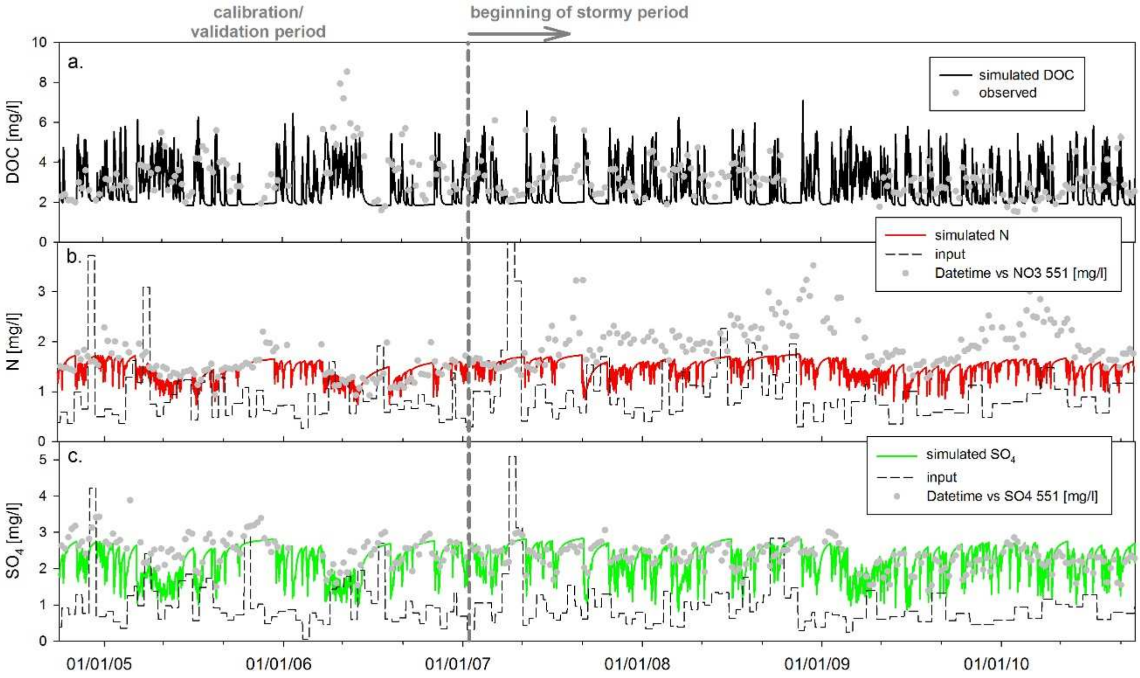

Figure 29: Observed versus simulated DOC, NO_3 and SO_4 at weir 1

7.4.2 Model performance during the stormy period

There is a deviation between pre-storm and stormy period simulated and observed variability and bias for N (Figure 30). A similar tendency can be found for DOC. But only the inter-annual ranges of the KGE components of N during the pre-storm period is small enough to be significantly different. The variations of DOC appear to be systematic, too, but they fall within its ranges of variability during the pre-storm period. For SO_4, there is only a significant trend to over-estimation concerning the bias.

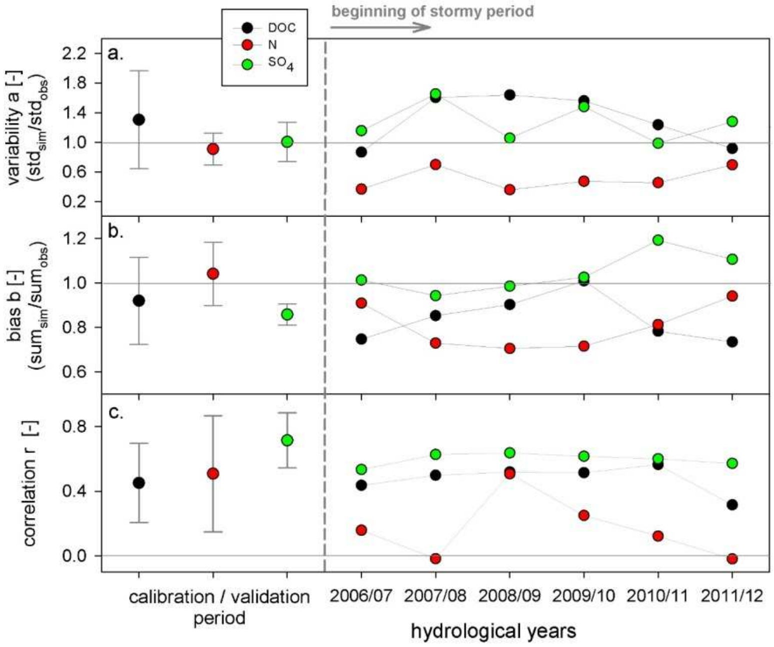

Figure 30: Indivudial components of the KGE: (a) ratio of simulated and obvsered variabilities, (b) ratio of simulated and observed average values, and (c) their correlkation for the stormy period; for comaprison the KGE components and their inter-annual variability are also shown for pre-storm period.

7.4.3 Adaption of N parameters for the stormy period

In a 1st scenario (Table 6), the model parameters for the N uptake and release are first adapted to compensate for the changes of N dynamics by enlarging the simulated N amplitude and equilibrium concentration, $Amp_{NO3}$and $Org_{mean,NO3}$,by a by the factor of maximum under-estimation of variability during the stormy period (Figure 30ab). Since the resulting increase of simulation performance was rather moderate, a further increase of performance was iteratively achieved by varying the three parameters systematically until the performance could not be improved further (2nd scenario). As indicated by the highest KGE (Table 6), scenario 2 provides the most acceptable adaption of the N dynamics to the impact of the storm (Figure 31). Its parameter values show an equilibrium concentration of N, more than two times larger than the pre-storm value, and amplitude around 4 times larger, and a phase shift towards almost 1.5 months earlier in the year (45 days earlier).

Table 6: calibrated pre-storm parameters for n dynamics and 2 scxenrios for adapting it at the stormy period

Parameter	Unit	Calibration type		
		Pre-storm	scenario 1	scenario 2
$Org_{mean,NO3}$	mg l^{-1}	0.97	1.4	2.3
PhS_{NO3}	d	341	341	21
Amp_{NO3}	mg l^{-1}	0.45	1.3	1.9
KGE_{NO3}*	-	-0.01	0.10	0.28

* for 2006/07-2011/12

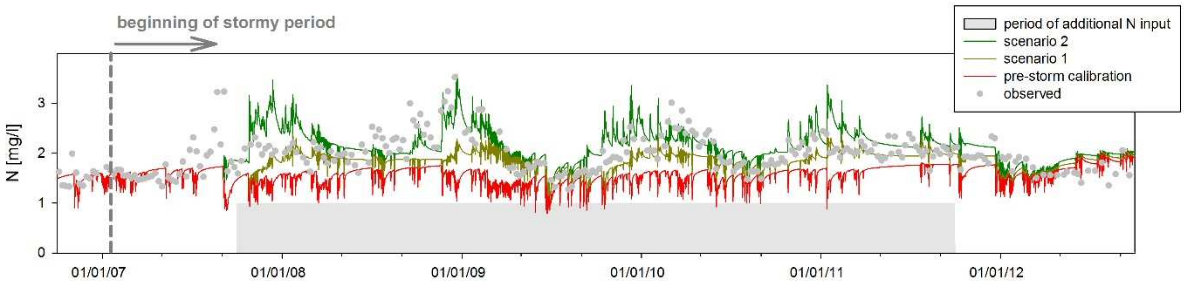

Figure 31: Observed and simulated N dynamics using the pre-storm parameters (red line), the scenraio 1 parameters derived from the deviations assessed by the KGE components (dark yellow line), and the scenraio 2 parameters derived by systematic varition (green line).

7.4.4 Transit time distributions

The transit time distributions indicate that the soil and epikarst system reacts quite rapidly to the changing input (some weeks) while large parts of the groundwater system need several months (Figure 32ac). Some of them even do not reach the mean concentration of the virtual tracer making the estimation of their mean transit times impossible. A similar distribution is found when the impact ends (Figure 32bd). It also shows that some of the simulated flow paths did not reach the input concentration before they started to decline again.

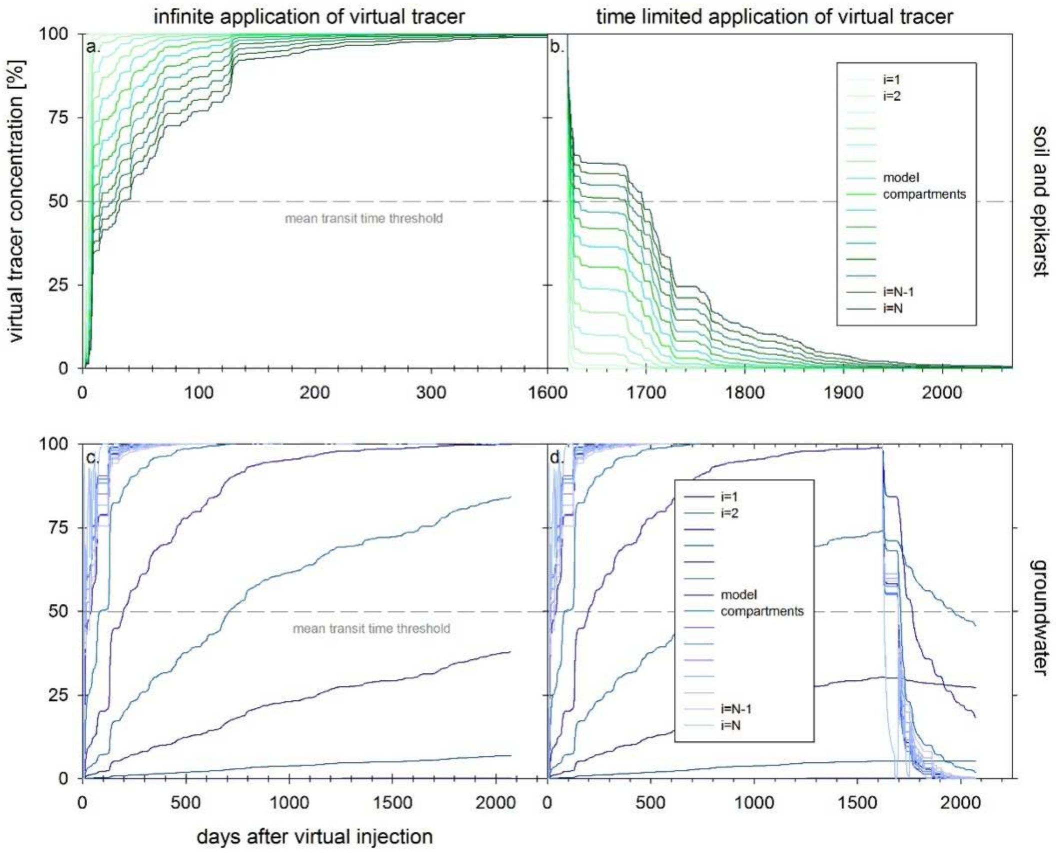

Figure 32: Mean transit times for (a) the soil and eipkarst and (c) the gorundwater storages derived by an infinit cvirtual tarcer injection strating with the beginning of the stormy period, and the reaction of (b) the soil and epikarst, and (d) the groundwater storage as the impact ends.

7.5 Discussion

7.5.1 Reliability of calibrated parameters and model simulations

Most of the calibrated model parameters are in ranges that are in accordance with other modelling studies or field evidence. With almost 3 weeks the epikarst storage constant is in accordance with field studies on the epikarst storage behaviour that found retention times of some weeks (Aquilina et al., 2006; Perrin et al., 2003b). The epikarst storage capacity is also in the range of previous findings (Perrin et al., 2003b) but with almost 500 mm the soil storage capacity is quite large considering mean soil thicknesses of only 50 cm at some locations at the plateau. Its high value may be explained by some structural errors of the model that result in unrealistic calibrated parameter values. However, the good multi-objective simulation performance of the mode, as well as its evaluation by parameter identifiaility analysis and the split sample test rather indicate that the overall performance of the model is acceptable. Since the soil controls the fraction of rain that is lost to evapotranspiration this high calibrated value might be due to tree roots ranging through the soil into the epikarst (Heilman et al., 2012) or rock debris (Hartmann et al., 2012a). Similarly to the epikarst storage constant, the conduit storage constant, K_C, is with its value of 1.1 days in the range of previous modelling studies (Fleury et al., 2007; Hartmann et al., 2013a). The high values of the epikarst variability constant and the groundwater constant indicate a low development of preferential flow paths in the rock, which is typical for dolostone aquifers (Ford and Williams, 2007). A low degree of karstification was already our study site (Jost et al., 2010) and the calibrated recharge areas fall well into the ranges found in previous modelling studies (Hartmann et al., 2012a, 2013c).

Also the hydrochemical parameters mostly show realistic values. A dissolution equilibrium concentration of ~0.4 mg/l for DOC and an average dissolution equilibrium concentration of ~1.0 mg/l for N are in a realistic range. The pre-storm phase shift indicates a maximum release of N at the time of the year when snow melt reaches its maximum (April) and when plants uptake activity is still low due to the end of the winter (Jost et al. 2011).The dissolution equilibrium concentration of 2.3 mg/l for SO4 indicates the abundance of evaporates in the system, which is a typical feature of karst systems (Goldscheider and Drew, 2007).

7.5.2 Impact of storm

The deviation between simulated and observed time series (Figure 29) already indicates that N is the only solute that shows a clear impact of the storms. This is further corroborated by considering the individual components of KGE in Figure 30. It is well known that nitrate leaching to the groundwater increases sharply after tree removal in forests where nitrogen is not strongly limited (Huber et al., 2005; Griffin et al., 2011; Bernal et al. 2012). Such disturbances disrupt tree N uptake, increase seepage fluxes and potentially increase nitrification so that high loads of nitrate is washed out from the soil. Since the simple N routine of the model cannot take into account such changes the model tends to under-estimate N concentrations and their amplitude. Similar trends were also found for DOC but its variations during the pre-storm period are similarly large, which prohibits further conclusions. The reason for the difference in the simulation precision of N and DOC may probably be due to a moderate representation of DOC processes. If so, calibrated model parameters have to compensate for model structure errors (Beven, 2006) and the simulation uncertainty increases.

N input

Adapting the N solute transport parameters only by the observed deviations that were indicated by the KGE components in Figure 30 resulted in a slight increase of performance (scenario 1). But increasing further the parameters for N contribution and its amplitude finally resulted in a significantly better N simulation performance than the pre-storm parameter set. An increase of the N equilibrium concentration of more than 1.3 mg/l indicates a massive mobilisation of N. By trial-and-error we identified the beginning of the impact at May 1st 2007 and its end by the end of the hydrological year 2010/11. This is more than 2 years after the last storm of the series and indicates the recovery period of the ecosystem. The shift towards an earlier maximum of N release (-45 days) may probably be due to the earlier onset of snow melt in open areas as compared to forests that drives the leaving of N towards the subsurface (Jost et al. 2011).

N propagation through the system

The virtual tracer injections that we performed with the previously identified beginning of the system elaborate the hydrological system's filter and retardation capacity. Due to their higher dynamics the soil and the epikarst system rapidly adapt to the change within weeks and months. Similar behaviour was also found in previous studies (Hartmann et al., 2012a; Kralik et al., 2009) But the groundwater system takes much longer. Even though the majority of the simulated flow paths adapts to the virtual tracer signal within some months a considerable number of them needs years to approach the virtual tracer's concentration. Some few do not reach it at all. Such slow pathways were also identified by water age dating analysis (Humer and Kralik, 2008; Kralik et al., 2009).

7.5.3 Implications

Our results corroborate findings from many other studies that extreme events as the stormy period with subsequent disturbances to the forest experienced at our study site from 2007 to 2008 can result in significant changes in N mobilisation. Such changes can happen quickly and prevail for a significant duration, in our case more than 2 years after the last storm. Due to subsurface heterogeneity the impact did not travel uniformly through the system. It rather split into different pathways and mixed with old water that percolated before the impact. In our system, large parts of the water travelled rapidly through the system. But a considerable number of pathways had large storages of old water and slow flow paths that did not adapt to the impact even after 4 years of duration. For the same reasons the surface mobilisation of N returned to its pre-storm value but elevated concentrations of N were still found at the monitoring station.

Taking into account that extremes like storms are more likely to occur in the future N mobilisation as observed in our study may occur more often and more intense. On the one hand the hydrological system may dilute and delay rapid shifts of N concentration. But on the other hand it will "memorize" the impacts for significant periods of time and it may not be recovered before the next storm mobilizes the next load of N.

7.6 Conclusions

In our study we used a process-based semi distributed karst model to simulate DOC, N and SO_4 transport through a dolomite karst system in Austria. We calibrated and validated our model during a 4-year time period just before a series of heavy storms caused strong damage to the study site' ecosystem. To quantify the impact of the storms we run the model for the entire stormy period using the parameters we found at the pre-storm period. The deviations between the simulations and the observations gave us indication that there was a significant shift in N mobilisation, its seasonal amplitude and its timing. Having estimated the beginning and end of the stormy period we applied a continuous virtual tracer injection to obtain the mean transit times of the karst system during the stormy period. They showed us how the hydrological system filtered and delayed the impact induced change at the beginning and at the end of the stormy period.

Even though our study is only considering one site and one stormy period it already provides some generally applicable conclusions: (1) hydroclimatic extremes such as storms do not only create droughts of floods; they highly affect water quality; (2) a hydrological system can filter and delay surface impacts but it may also memorize past impacts and a higher frequency of impacts may result in superposition; (3) water quality models that have been calibrated without consideration of such external impacts will provide poor predictions. For these reasons we believe that future large-scale simulations of water resources have to include water quality simulations. Even without anthropogenic contamination climate change will strongly affect water quality in our aquifers and streams and we have to understand and prepare ourselves to avoid threads on future water supply

7.7 Acknowledgements

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7.8 Appendix

Snow routine

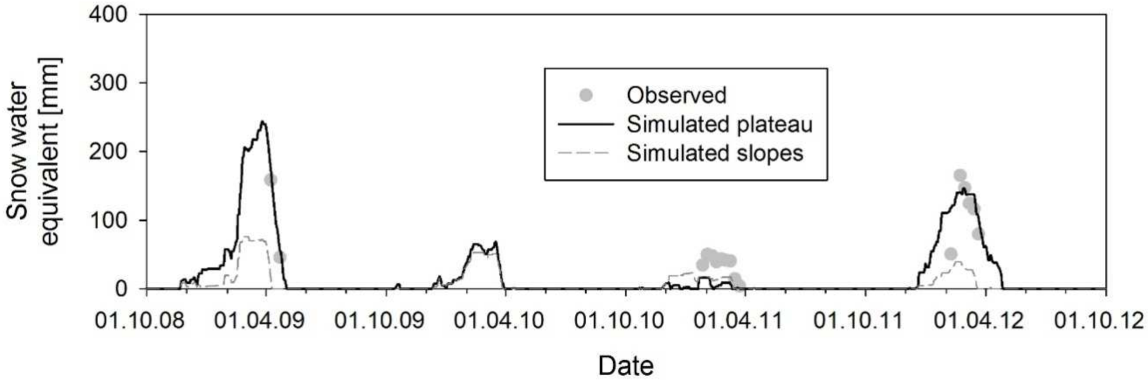

Figure 33: Observed versus simulated snow water equivalent for the plateau and the slopes; observations were taken at the plateau beside the precipitation station (Figure 26)

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8. Annex 5

Complementary analyses - Forest growth modelling at LTER-Zöbelboden

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8.1 Objectives

Forests are recognized and expected more and more suffering from climate change and variability because of their high dependence on weather regime (especially temperature and precipitation) to sustain growth and maintenance, as well as to allow recovery after disturbances or meteorological extreme events. An additional model-based analysis was performed at Intensive Plot 1 (IP1) of LTER Zölbelboden site, in order to assess and project the impacts of new climate regime on carbon and water fluxes regulating forest growth and resilience. The outcomes of this study are a further example of useful analyses when aiming to consider climate change in designing and implementing adaptation strategies within forest management and protection plans.

8.2 Data and methods

The additional analyses performed at IP1 consisted first of all in calculating climate indicators based on simulated variables (maximum and minimum temperature and precipitation) from bias-corrected RCM COSMO-CLM (http://www.clm-community.eu/) runs performed along 1971 to 2005 under 20C3M GHG forcing (http://www.ipcc-data.org/ar4/scenario-20C3M.html), and along 2006 to 2070 under RCP4.5 and RCP8.5 forcings (IPCC-AR5; http://sedac.ipcc-data.org/ddc/ar5_scenario_process/RCPs.html); in all cases the boundary conditions were set by CMCC-CM GCM. Bias-correction of these model simulations was performed applying the method of Sperna-Weiland et al. (2010), reducing the threshold for the multiplicative factor from 10 to 4 according to previous analyses on the same data for the simulation domain. Selected climate indicators are: APA, MAmaxT and MAminT, PRCPTOT, R50mm and CDD (See Annex 7).

Successively, daily data for precipitation, maximum and minimum temperature, relative humidity and solar radiation from above bias-corrected simulations, extracting the model grid point closest to the IP1 site, were used to drive runs of the 3D-CMCC Forest Ecosystem Model (Collalti et al. 2014). 3D-CMCC-FEM has the advantage to be a dynamic process-based model to simulate growth, carbon allocation, and forest dynamics in heterogeneous populations. Daily eco-physiological processes that govern GPP, NPP, and dynamics of carbon stocks, structure of the population, of the biomass pools, soil and climatic conditions are considered in the model. The same initialization than L-DNDC (see main text) for the Spruce dominated forest of IP1 was adopted. In particular model has been set to reproduce, in addition to the other processes above described, competitive processes (i.e. for light and water) between the two cohorts and the two layers (i.e. dominant and dominated) that reflect the IP1 stand: the dominant layer is composed by a 115 years old of Picea abies, the dominated layer is composed by Fagus sylvatica.

To rely on climatologically significant (25-30 years) length of simulated periods to be analysed and compared, model runs were designed as follows:

- Control RCP 4.5 simulation (CTL4.5): it consisted of an initial 25-year "actual-synthetic" period 1996-2020, representative of the current conditions, generated by repeating from 2011 to 2020 daily observed meteorological series for 1996-2010, and then continuing with 2021-2070 data from RCP4.5 driven climate projections simulations.

- Control RCP 8.5 simulation (CTL8.5): as above, but continuing with 2021-2070 data from RCP8.5 driven climate projections simulations.

- Model-based RCP 4.5 simulation (MOD4.5): it consisted of an initial 25-year "actual-synthetic" period 1996-2020, representative of the current conditions, generated by repeating from 2006 to 2020 daily modelled meteorological series for 1996-2005, and then continuing with 2021-2070 data from RCP4.5 driven climate projections simulations.

- Model-based RCP 8.5 simulation (MOD8.5): as above, but continuing with 2021-2070 data from RCP8.5 driven climate projections simulations.

Model outputs of interest are represented by four indicators of forest status: GPP, NPP, AR and CE (See Annex 7). To allow consistent evaluation climate sensu, all indicators have been averaged along medium term (2021-2050) and long term (2041-2070) periods to be compared to the average of "actual-synthetic" period (1996-2020, representing current conditions).

Given that the model grid point, although being the closest to IP1, can have different characteristics (e.g. topographic attributes) than IP1, the anomaly/bias between MOD and CTL during 1996-2020 served to adjust the successive MOD simulation period (2021-2070) for the bias detected in the actual-synthetic period. This was made easier by the fact that the 1996-2020 results between the two CTL simulations are equivalent, as well as those between the two MOD simulations, as not affected by RCP emission scenarios. Then, for the 2021-2070 time frame, the average of the two RCP (4.5 and 8.5) simulations was considered both for the medium and the long term periods, since assumed representative of the uncertainty spread related to the emission scenarios.

8.3 Results

Climate indicators of maximum and minimum temperature (Figure 34a) confirm what found in terms of expected temperature trends from SRES ensemble simulations reported in the main text. In particular, on an annual average, the maximum and minimum temperatures (MAmaxT and MAminT, respectively) are expected to increase by 0.7 and 0.9°C respectively for the medium term period, and by 1.9 and 2.0°C respectively for the long term period. Moreover, the recognized uncertainty in precipitation is confirmed by the fact that the average of RCP-driven simulations, while confirming a drying trend in summer (but only in the long term), project the same also for winter (in both future periods and opposite than in SRES-based results); spring and autumn are expected to become wetter (Figure 34b). On an annual average, both APA and PRCPTOT indicators suggest an increase for precipitation in the medium term and a decrease in the long term. Finally, indicators like R50mm and CDD suggest an increase of extreme events, with more frequent intense precipitation days and longer periods of dry days.

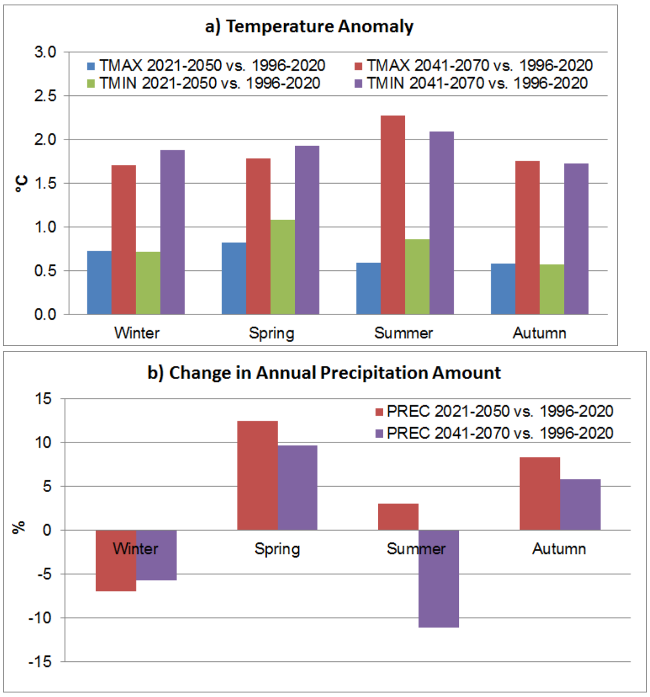

Figure 34 a) Anomalies (°C) of seasonal maximum and minimum temperatures (TMAX and TMIN) for the medium term (2021-2050) and long term (2041-2070) periods vs. the current 1996-2020; b) Anomalies (%) of seasonal precipitation (PREC) for the medium term (2021-2050) and long term (2041-2070) periods vs. the current 1996-2020.

3D-CMCC-FEM outputs driven by daily series of above climate projections predict significant changes in forest processes in terms of productivity and water fluxes, with drop of all the considered indicators on the order of 20-25% on the medium term, and around 35-40% on the long term (Figure 35).

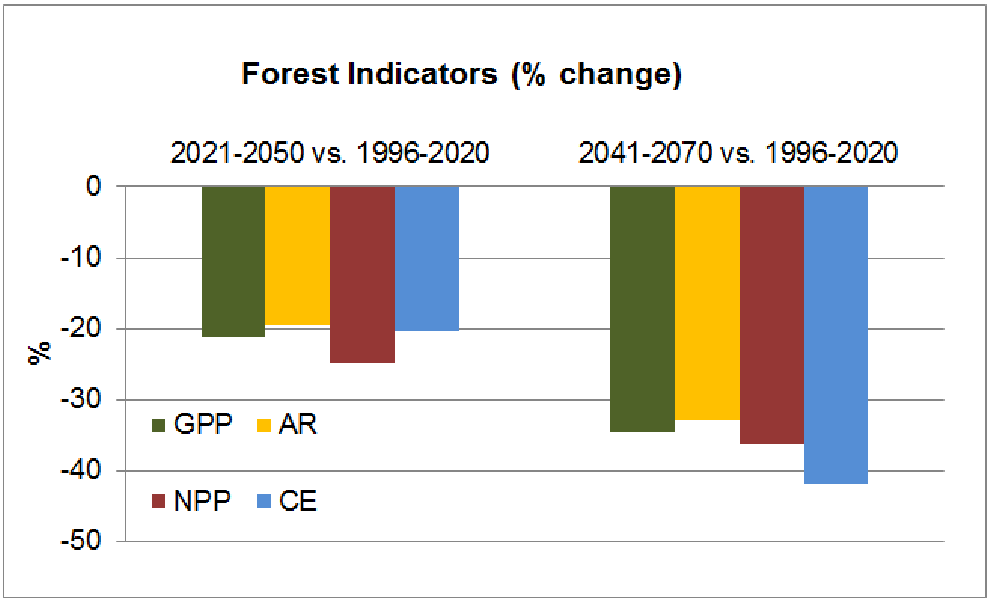

Figure 35 Anomalies (%) of annual GPP, AR, NPP and CE for the medium term (2021-2050) and long term (2041-2070) periods vs. the current 1996-2020.

All simulations show remarkable changes in seasonal growth. For both Spruce and Beech there is an increment in the days of “full” growth due to an anticipated beginning of photosynthetic activity (bud burst phase) and a postponed end (litterfall phase). This is counterbalanced in the late spring, summer and early autumn. This trend is mainly related to the new climate regime (with higher temperature and fluctuating trends of precipitation) during the years of simulations. In addition there is a strong mortality reduction, due to crowding competition, for the beech layer during the first years of simulation, this behaviour seems however mainly related to forest structure in IP1 (a very dense dominant layer of Spruce trees), up to determine a complete absence of beeches at the end of simulation (none regenerations processes has been considered in this study).

8.4 Conclusive remarks

The expected climate regime for the LTER-Zöbelboden site is projected to exacerbate over time the fragile forest ecosystems, in terms of water quality and quantity (see main text), as well as for productivity and biodiversity maintenance. The less prosperous vegetation could be also more vulnerable and less resistant to additional climate-related disturbances like fires and pest infestations.

Very high resolution and most updated climate projections have been used in this complementary study; they are based on two RCP emission scenarios, comprising the less optimistic RCP8.5 and the intermediate RCP4.5. Even if this could benefit a precautionary assessment, in any case the usage of single (COSMO-CLM) model ensemble and of only two members (RCPs) of the ensemble limit the analysis to a very narrow bound estimate of impacts.

However, the complementation of the principal analysis based on L-DNDC with additional evaluations using an alternative approach like 3D-CMCC-FEM is a preliminary step toward a better representation of ecosystem complexity, by enlarging the set of impact indicators.

Moreover, both climate simulation data, modelling tools and synthesis indicators need to be tailored in order to: become easily available and useable by technicians of e.g. forest offices, environmental agencies and other stakeholders; allow translating scientific results into understandable highlights on vulnerability and risk; and guiding the inclusion of feasible and comprehensive adaptation options into forest management planning.

8.5 References

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9. Annex 6

Water Protection Functionality Index (WPFI)

(Koeck R. and Hochbichler E.)

Water Protection Functionality Index (WPFI) describes the contribution of a forest stand or a forest ecosystem to the provision of the ecosystem service ‚Drinking Water Protection‘. ‘Drinking water protection’ (DWP) was specified as ‘provision of high quality drinking water in adequate quantity for water supply’. Forest ecosystems can provide a high level of DWP, if they are treated according to the specific guidelines for drinking water protected areas. This requires adaptive forest management on all levels of silvicultural interventions. Recommendations and guidelines were formulated by Koeck and Hochbichler (2014). If inadequate forest management practices are applied, the water protection functionality can be diminished, in some cases even be destroyed.

For the assessment of the WPFI in the pilot study area 1 of the OrientGate project, the available forest parameters of the simulation runs (Landscape DNDC model simulations) were integrated. Those are (1) the silvicultural technique applied at the pilot study area, (2) the target tree species composition of the simulation run and (3) the regeneration dynamics. If further data would have been used for the model simulations, also further parameters would have been applied for the calculation of WPFI. The three parameters which were actually used can be described as the most important ones for defining the WPFI of a forest stand.

The assignment of the WPFI values was carried out for the defined management scenarios of the Landscape DNDC model simulations. Basis for the value assignment for the three forest parameters was the elaborate ‘Recommendations for Adaptive Management Concepts’ (Koeck and Hochbichler 2014), where Best Practices for forested drinking water protected areas were defined.

WPFI is calculated as normalized value of the three applied forest parameters. The range of the WPFI values and their indication are described in Table 7. A high water protection functionality of a forest stand is given, if WPFI ranges between 0.8 and 1.0. A very low WPFI value between 0 and 0.29 indicates, that the water protection functionality of a forest actually is a very low (Table 7).

Table 7: WPFI values and the WPFI indication.

WPFI Value	0.8 – 1.0	0.5 – 0,79	0.3 – 0,49	0 – 0.29
WPFI Indication	high	medium	low	very low

9.1 Calculation of WPFI as normalized value

$$\mathrm{WPFI} = (\mathrm{SiTe} + \mathrm{TrSp} + \mathrm{ReDy}) / 3$$

WPFI	Water Protection Functionality Index (normalized)
SiTe	Parameter ‘Silvicultural Technique applied in the DWPA’
TrSp	Parameter ‘Tree Species distribution in relation to the natural forest community’
ReDy	Parameter ‘Regeneration Dynamics’

9.2 WPFI calculation with three categories of forest parameters

+ Parameter-WPFI of the Applied Silvicultural Technique (SiTe) (Table 8**)**

- Clear-Cut Management (CCM) (more than 0.4 ha up to 2 ha in Austria, upper limits may be higher in other countries). Application of large clear-cuts receives a Parameter-WPFI of 0.0 as it endangers significantly related drinking water resources.
- Shelterwood Cut Management (SCM): Clear-Cut phase 5 years after a strong stem reduction (50 %): The fact, that after 5 years a clear-cut phase is involved again, the Parameter-WPFI is only reaching the value of 0.1. This is related to the strong destabilization of the forest stand due to the 50 % stem reduction and the subsequent clear-cut phase only five years after the first cut.
- Continuous Cover Forest Management (CFM) with target diameter harvest (> 50 cm): In the case of CFM the forest functions are provided over space and time and for the initialization of regeneration only small gaps are created as consequence of the target diameter cutting measures, which only involves single-tree or group-cutting. The assigned Parameter-WPFI of 0.8 is relatively high. CFM already provides higher forest stand stability than the other two techniques. But only group selection cutting with the target of forest stand stabilization (cutting of instable trees) would reach the highest value of 1.0.

+ Parameter-WPFI of Tree Species in relation to the natural forest community (TrSp) (Table 8**)**

- The natural forest community at the test site is the Hordelymo-Fagetum.
- Within this specific forest community a dominance of European beech (Fagus sylvatica) is given, mixed species are Silver fir (Abies alba), Sycamore maple (Acer pseudoplatanus), ash (Fraxinus excelsior, at lower elevations), sporadically tree species are Norway spruce (Picea abies), yew (Taxus baccata) and holly (Ilex aquifolium). As silviculturally established tree species or as pioneer species after large-scale disturbances also European larch (Larix decidua) can occur.
- 100 % of Norway spruce within this forest community causes a destabilization of the forest stands (bark-beetles, wind-throw and snow-damages). The Parameter-WPFI hence is only o.1 in the case of SCM and only 0.0 in the case of CCM (Table 8).
- 50 % spruce and 50 % beech are more stable than a pure spruce stand, but still do not cover the requirements of the Hordelymo-Fagetum, which naturally involves a beech dominance and also further tree species. The Parameter-WPFI in this case was assigned with the value 0.7.

+ Parameter-WPFI of Regeneration dynamics (ReDy) (Table 8**)**

- Understorey regeneration dynamics either occur as natural regeneration process or are created by silvicultural interventions as part of artificial recruitment activities. Trees stemming from natural regeneration are rated higher in terms of stability than trees stemming from artificial recruitment activities. Hence the natural regeneration dynamics of the CFM was rated with the high value of 0.8 as it involves both spruce and beech (Table 8). The SCM value of 0.4 is lower, as it involves only spruce but natural regeneration. The CCM value of 0.2 is caused by the fact, that only spruce is planted artificially.

- If the regeneration would show grave browsing damages, a value of 0.0 would be assigned. Hence it was assumed that there did not exist browsing damages created by wild ungulates. In contrast the highest potential value of 1.0 would only have been assigned for a higher share of beech and further tree species, like maple or fir in the natural regeneration phase, what would reflect the natural tree species diversity in regeneration.

Table 8: Parameter-WPFI for the single forest parameters used in the Landscape DNDC simulations.

Silvicultural Technique (SiTe)	**Tree Species Composition (TrSp)**	**Regeneration Dynamics (ReDy)**
CFM 0.8	Spr/Bee 0.7	Natural 0.8
SCM 0.1	Spr 0.1	Natural 0.4
CCM 0.0	Spr 0.0	Artificial 0.2

9.3 Overall normalized WPFI calculation

CFM: WPFI = (0.8 + 0.7 + 0.8) / 3 **WPFI (CFM) = 0.767**

SCM: WPFI = (0.1 + 0.1 + 0.4) / 3 **WPFI (SCM) = 0.200**

CCM: WPFI = (0.0 + 0.0 + 0.2) / 3 **WPFI (CCM) = 0.067**

The overall WPFI calculation shows, that the forest management scenario CFM is related to a medium WPFI (water protection functionality index). Both SCM and CCM are related to a very low WPFI, as they endanger the water resources through clear-cut phases (see Table 7and Table 8 for the explanation of the values).

9.4 Appendix

Table 9: Forest management options. CFM: continuous forest cover spruce-beech management; SCM: shelterwood-cut management; CCM: clear-cut management.

	Target tree species	Overstorey thinnings	Final harvest	Understorey regeneration
CFM	Norway spruce (50%), European beech (50%)	Target diameter harvest at 50 cm dbh	no	natural
SCM	Norway spruce (100%)	Thinning to 400 trees/ha at 10, 25, 40 years	50% stem reduction at 115 years; total harvest at 120 years	natural
CCM	Norway spruce (100%)	Thinning to 400 trees/ha at 10, 25, 40 years	100% harvest at 120 years	planting (2500 trees/ha)

9.5 References

Koeck, R., Hochbichler, E. (2014). Appendix 1 – Recommendations for Adaptive Management Concepts – Best Practices for Forest Ecosystems in Mountains and Flatlands. To be downloaded at: www.ccware.eu under Output Documentation, WP4.

10. Annex 7

List of Indicators

Short Name	Long Name	Short description
R50mm	Precipitation days with RR ≥ 50 mm	Precipitation days with a daily amount (RR) ≥ 50 mm. Count the number of days in chosen period (during growing season; other season)
PRCPTOT	Total precipitation in wet days	Precipitation amount on days with RR ≥ 1 mm in a chosen period (e.g. year)
SWE	Snow water equivalent	measurement of the amount of water contained in snow pack
SPI12	Standardized Precipitation Index	see WP 3 description
CDD	consecutive dry days	see WP 3 description
WPFI	Water protection-Forest-Index	Forest stand and soil indicator which describes the functionality of forest ecosystems for water protection
GPP	Gross Primary Production	It denotes the total amount of carbon fixed in the process of photosynthesis by plants in an ecosystem, such as a stand of trees. GPP is measured on photosynthetic tissues, principally leaves.
NPP	Net Primary Production	It denotes the net production of organic matter by plants in an ecosystem-that is, GPP reduced by losses resulting from the respiration of the plants (autotrophic respiration).
AR	Autotrophic Respiration	Autotrophic Respiration (or plant respiration) represents the photosynthetically fixed carbon that is lost by internal plant metabolism.
CE	Canopy Evapotranspiration	It is the sum of evaporation and transpiration from forest canopy.
MAmaxT	Mean Annual maximum Temperature	The average of the maximum temperature for the year.
MAminT	Mean Annual minimum Temperature	The average of the minimum temperature for the year.