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Long-term monitoring in the Große Ohe catchment, Bavarian Forest National Park

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Abstract
In 1977, a long-term hydrological monitoring program was launched in the Große Ohe headwater catchment inside the Bavarian Forest National Park. It has been operated by Bavarian state institutions, which reliably ensure high quality measurements. The main aim is to document and investigate changes in water cycling during, and due to, the transition from commercial to near-natural forest under strict protection and non-intervention policy. Moreover, it constitutes the basis for further monitoring activities. The landscape here is remote from strong sources of air pollution but its ecosystems are highly vulnerable to air pollutants. Therefore, the state and federal agencies for environmental issues used this background to implement their own monitoring programs aiming at the effects of transboundary air pollutants on the ecosystem in the Forellenbach subcatchment and groundwater quality in the Markungsgraben subcatchment. The whole of hydrological and hydrobiogeochemical information resulting from this nested approach has been very helpful to cope with the public concern and political pressure related to disturbance effects on ecosystem services. Here we shortly describe catchment characteristics, measuring sites, and methods used of the respective monitoring programs, and present some relevant results and references to highlight their scientific and political value.

Key words: natural disturbance, air pollution, ecohydrological and hydrobiogeochemical processes

Introduction

According to international perceptions about the main aims and purposes of National Parks, the advisory board noticed in 1970 that research and monitoring of ecosystems and ecosystem functioning is a primary goal to be realized in the Bavarian Forest National Park (Braun et al 1999). The implementation of a hydrological monitoring program started in 1975. This was in full accordance with the objectives of the International Hydrological Decade (UNESCO-WMO-IAHS 1974), keeping in mind that, in Bavaria, monitoring of forested catchments was lacking at that time. In 1977, seven years after the National Park foundation, measuring activities were launched in the Große Ohe catchment.

The main aim of this program is the long-term monitoring of the water cycle with: (i) the investigation of changes in characteristics of runoff (e.g. total runoff volume, peak discharge, frequency of peak flows) in a forested catchment during and due to the transition from commercial to near-natural forest without management intervention; and (ii) the long-term documentation of the water cycle in a near-natural catchment providing reference data for the assessment of anthropogenic impacts in managed areas (Gietl 1989).

The responsibility for implementation and operation has been defined in an administrative agreement between the cooperating authorities (present status) as follows:

- The Bavarian State Institute of Forestry (LWF): climate station, precipitation and snow cover network, data management and analysis.

- The Bavarian Environmental Agency (LFU): discharge and runoff water quality at the stream gauge, technical and building maintenance, data management and analysis.
- The Technical University of Munich (TUM), Department of Bioclimatology: coordination and up-dating of research activities (dormant/suspended).
- The Bavarian Forest National Park (NPBW): all field work, e.g., data acquisition, sampling, maintenance of infrastructure (technical maintenance, data analysis).

The Forellenbach subcatchment of the Große Ohe catchment is a part of the International Cooperative Program on Integrated Monitoring of Air Pollution Effects on Ecosystems (UN ECE IM) within the framework of the Geneva Convention (http://www.unece.org/env/lrtap/) on Long-Range Transboundary Air Pollution. Since 1990, the Federal Environment Agency (UBA) and Bavarian Forest National Park Administration (NPBW) have been carrying out this monitoring program in the Forellenbach catchment, which is remote from significant sources of emission and solely subject to transboundary air pollution. Together with the catchments of Lysina and Anenské Povodí in the Czech Republic and Zöbelboden (National Park Kalkalpen) in Austria, it belongs to the network of 42 monitoring sites in 13 countries of the Northern Hemisphere (status 2015, http://www.syke.fi/nature/icpim).

The main aims of this program are (i) to document the state of ecosystems and the changes caused by anthropogenic impacts, such as atmospheric pollutants (acidifying compounds, nutrient nitrogen, ozone, heavy metals), and climate change; and (ii) to provide scientific and statistically reliable data in order to establish consistent time series for environmental variables that can be used in modelling and decision making.

These objectives require long-term observation of physical-chemical parameters and of biotic components of ecosystems that indicate environmental changes: meteorological parameters and pollutants in ambient air (SO_2, NO_x and O_3); water and element cycles in beech and spruce stands and at the catchment level; vitality and growth of single trees, forest stands, and understorey vegetation; and stock of brown trout.

Since 1987, the LFU has been monitoring water and element fluxes in the Markungsgraben subcatchment in the Bavarian Forest National Park, as part of its measuring network "Atmospheric input – ground water quality" (MSGw). Originally, this cross-media program focused on the effects of atmospheric inputs of acidifying compounds on drinking water quality (Moritz et al. 1994). The Integrated Hydrological Modelling (IHM) is continuing this program with the main objectives to document the water and element cycles in extensively used or protected areas and to identify possible effects on water supply. Particular attention is paid (LFU 2015) to the effects of (i) climate change on the quantity and quality of water, (ii) land use changes including natural disturbances, and (iii) input and mobilising of harmful substances.

Sites and methods

Long-term hydrological monitoring in the Große Ohe catchment†

The Große Ohe headwater catchment is 19.1 km² in size and its altitudinal range is from 770 m (the gauge Taferlruck: 48°56'17.99" N, 13°24'45.13" E) to 1453 m a.s.l. (Mt. Großer Rachel). The catchment is 98% forested, with Norway spruce (*Picea abies* (L.) Karst., 70%) and European beech (*Fagus sylvatica* L.) being the dominant species. Since 1992, bark beetle (*Ips typographus* L.) killed spruce forests on 58% of the catchment area and converted them into varying early succession stages with rapidly growing young spruce. The physiographic

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Table 1. Physiographic and hydrometeorological catchment characteristics (BEUDERT et al. 2015, modified). Mean air temperature covers 1980–2004, mean precipitation and runoff cover 1992–2010 (minimum and maximum values in parentheses). Norway spruce dominates the tree species composition (status 1990), while European beech is the dominant broadleaf species; the combined contribution of other species is less than 5%.

Stream: Characteristics	**Große Ohe catchment**	**Markungsgraben subcatchment**	**Forellenbach subcatchment**
Area (km²)	19.1	1.1	0.7
Elevation (m a.s.l.)	982 (770–1447)	1128 (890–1355)	894 (787–1293)
Slope (°)	11.1	16.1	8.4
Bedrock	biotite granite, cordierite-sillimanite gneiss	biotite granite, cordierite-sillimanite gneiss	biotite granite
Soils (%)			
Lithosols, rankers	16	38	12
Cambisols, podzols	60	50	58
Histosols, gleysols	23	12	30
Tree species	Norway spruce (70%), broadleaves	Norway spruce (84%), broadleaves	Norway spruce (69%), broadleaves
Air temperature (°C)	5.5	5.3	6.2
Precipitation (cm)	162 (129–227)	176 (141–230)	160 (127–221)
Runoff (cm)	106 (72–157)	135 (90–172)	105 (76–145)

and hydrometeorological catchment characteristics are shown in Table 1, which also includes information about the two nested catchments, that represent the upper slopes (Markungsgraben, 1.1 km²) and the lower slopes (Forellenbach, 0.7 km²) (Fig. 1). The hydrological monitoring in the Große Ohe catchment was launched in 1977, while the IHM and UN ECE-IM started in 1987 and 1990, respectively. For information about the latter monitoring programs whose hydrological parts contribute significantly to the Große Ohe database, see the respective sections below.

The monitoring program in the Große Ohe catchment comprises precipitation measurements to derive catchment precipitation, snow depth and snow water equivalent courses to estimate snow cover and above surface water storage and discharge measurements to complete the data base for calculating catchment balances. Information on groundwater level and quality come from IHM and UN ECE-IM stations.

Precipitation

There are different bucket types in the field which are designed to catch precipitation over different intervals for different purposes.

From 1979 to 1989, daily precipitation was measured using 53 Hellman type buckets at 2 m height covering the whole catchment in order to describe the spatial distribution of precipitation yields and to test different approaches to estimate mean catchment precipitation (Fig. 1, TEICHMANN 1984, THUMS 1991).

Catchment precipitation is calculated according to KLÖCKING et al. (2005) using precipitation records of six out of eight monthly totalising samplers (Fig. 1, TEICHMANN 1984, THUMS 1991). The recording locations span an altitudinal range from 770 m to 1360 m a.s.l. These samplers are constructed to prevent upwind effects on sampling efficiency. In addition, water is prevented from evaporation by oil coverage during summer and from icing by adding solid calcium chloride during winter. Complete quality checked data of single samplers and catchment precipitation cover January 1980 up to now.

Beginning in the early 2000s, weighing type precipitation recorders have been successively installed at those locations where monthly totalising samplers are operated. This design enables to study the rainfall intensity and allows for comparison and cross-validation of the equipments, at least during snow-free periods.

Snow depth and snow water equivalents

In 1978, a snow course has been established (Fig. 1) consisting of graduated (10 cm resolution) and calibrated snow stakes fixed on permanent open sites representing the topographic characteristics of the catchment with respect to elevation and aspect (Teichmann 1984, Stang 1988). In 1994, the snow course has been reduced from 53 to 33 stakes. The locations fulfil the WMO (2008) requirements for precipitation sites. Measurement of snow depth (5 cm accuracy of the estimate), accounting for the effects of snow melting or accumulation immediately surrounding the stake, is repeated in regular intervals of two weeks.

In 1978, the second snow course has also been established consisting of 12 forests stands (7 plots Norway spruce, 5 plots European beech) to investigate species specific differences in snow dynamics (Fig. 1). The stands follow the altitudinal gradient pairwise from 802 to

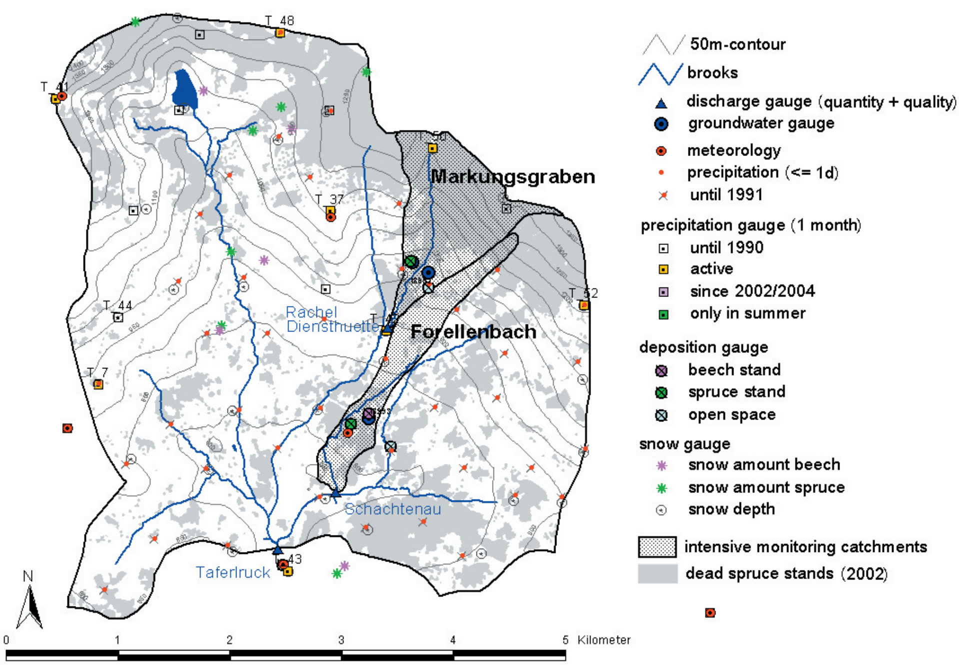

Fig. 1. Topographic map of the Große Ohe catchment (Klöcking et al. 2005, modified) and the nested Forellenbach and Markungsgraben intensive monitoring catchments (grey dotted), displaying the extent of dead Norway spruce stands in 2002 (grey area), and the locations of precipitation, snow depth and snow density networks, ground water boreholes, stream gauges, meteorological stations, and the intensive monitoring plots of IHM and UN ECE-IM. Contour lines represent the elevation above sea level (m a.s.l.). For catchment characteristics see Table 1, for the design of monitoring activities see Tables 2 and 3.

1323 m a.s.l. in the centre of the catchment. The snow sampling equipment consists of a Teflon coated aluminium tube (cross-sectional area 25 cm^2) and a spring balance. Height and weight records of 10 snow samples are averaged to compute mean height, snow water equivalent, and density of snow for each date and location. From 1997 to 2001, spruce stands on all snow plots were killed by bark beetle changing forest structure (canopy closure) to early succession stages, while beech stands remained unaffected.

Discharge and runoff water chemistry

In 1977, continuous water level measurements in the Große Ohe stream have launched at the Taferlruck stream gauging station using a pressure sensor. The artificial and geometrically defined flume is split into a small part enabling low flow and a large cross section for high flow measurements (Fig. 2). Up to now, instantaneous flow varied between 0.09 and 24 $m^3.s^{-1}$. Independent discharge measurements with a current meter are conducted to check the rating curve. Both historical and present discharge data are available at www.gkd-bayern.de (Bavarian Hydrological Service).

Temperature, pH, oxygen content and electric conductivity are measured continuously and registered every minute. Samples for chemical analysis are taken manually every two weeks and analysed for major and some minor components according to DIN/EN/ISO methods in the laboratories of LFU.

Fig. 2. The Taferlruck stream gauge (48°56'17.99" N, 13°24'45.13" E) with a cross section designed for low and high flow measurements (photo: W. Breit, 2015). Independent discharge measurement with a current meter is performed using the wooden bridge. Note that, up to now, the instantaneous flow varied between 0.09 and 24 $m^3.s^{-1}$. In 2010, the downstream channel underwent reconstruction to reduce its barrier effect on fish migration.

Groundwater level and chemistry

Since 1987, groundwater level has been measured in three observation boreholes (Fig. 1). Two of them are located in the middle slope of the catchment (970 and 980 m a.s.l.) representing the deep, slow flowing aquifer. The third is located in the lower slopes (810 m a.s.l.) representing the fast flowing aquifer in solifluction layers and *in situ* weathered regolith. Beginning in the early 2000s, manual measuring of stage height has been replaced by pressure sensors with hourly registration. Physical and chemical data are taken from the Forellenbach (UN ECE-IM) and Markungsgraben (IHM) monitoring programs (see the respective sections below).

Climate

During the 1980s, a climate station was established near the Taferlruck gauging station (Fig. 1). It is used as a reference for valley locations, which are characterised by frequent late frosts in spring and early frosts in autumn. Meteorological instruments are mounted on a 10 m mast at standardized heights according to WMO (2008) requirements. Sensors for wind speed and wind direction are fixed at the top; insolation, air temperature, and humidity sensors are clamped on arms at 2 m. Soil temperature is measured in several depths down to 100 cm. Sensor readings are stored every 10 minutes. Further climate data are taken from the NPBW station Waldhäuser (945 m a.s.l., 48°55'45.89'' N, 13°27'53.28'' E) and from climate models (Klöcking et al. 2005).

Data availability

Recorded data and metadata are available since 1977 upon request in Excel spreadsheet or data base format from the respective supervisors: climate, precipitation, snow depth and snow water equivalents (LWF), discharge and runoff water chemistry (LFU), ground water level and chemistry (LFU, NPBW). There are no larger or systematic gaps in data series.

Integrated monitoring (UN ECE-IM) in the Forellenbach catchment†

The Forellenbach subcatchment (Table 1) is 0.7 km² in size and the altitudinal range is from 787 m (the gauge Schachtenau, 48°56'33.61'' N, 13°25'10.63'' E) to 1292 m a.s.l. (Bärenlochriegel). The catchment is 99% forested, with Norway spruce (69%) and European beech being the dominant species. It covers predominantly middle and lower slopes in the Große Ohe catchment, adjacent to the Markungsgraben subcatchment. Further physiographic and hydrometeorological catchment characteristics are shown in Table 1.

The subprograms of Integrated Monitoring are shown in Table 2, which also describes the character of locations (station or plot), its name and elevation. Abbreviations in brackets correspond to program codes according to the "Manual for Integrated Monitoring" (http://www.syke.fi/nature/icpim). Physical and chemical parameters, field methods and sampling procedures are in full accordance with international standards described in this manual. Water and organic material, as well as mineral soil is analysed for major and some minor components according to DIN/EN/ISO methods (http://www.syke.fi/nature/icpim) in the laboratory of LWF. Only site-specific information is given below.

Intensive monitoring plots

Most of water, biomass and tree related subprograms have been performed in two beech stands and two Norway spruce stands (Fig. 1). In 2008, the mature beech stands B1 and B2 (Table 2) had timber stocks of 390 and 467 $m^3.ha^{-1}$, respectively. The spruce stand F1 Schachtenau (1995: 1000 $m^3.ha^{-1}$) died completely in 1996, changing the forest canopy from

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Table 2. Subprograms of the Integrated Monitoring program (UN ECE-IM) in the Forellenbach catchment together with the number, elevation and size of measuring stations and intensive plots. Abbreviations in brackets correspond to program codes according to the Manual for Integrated Monitoring (http://www.syke.fi/nature/icpim).

Plot/Station		**Elevation**	**Size**	**Subprogram (code)**
Name	Nr	(m a.s.l.)	(ha)	
Schachtenau	1	787		Runoff chemistry (RW)
	2	820		Groundwater chemistry (GW)
	10	857		Air chemistry (AC)
Weitau	13	810		Precipitation chemistry (PC)
Taferlruck	14	770		Precipitation chemistry (PC)
B1 beech	40	820	0.24	Throughfall, (TF), Soil water chemistry (SW), Litterfall chemistry (LF)
	46	825	0.04	Microbial decomposition (MB), Soil chemistry (SC)
	60	820	0.25	Tree bioelements (BI), Vegetation (VS)
	71	820		Foliage chemistry (FC), Forest Damage (FD)
B2 beech	65	980	0.25	Tree bioelements (BI), Vegetation (VS), Forest Damage (FD)
	66	990	0.04	Microbial decomposition (MB), Soil chemistry (SC)
	67	1010		Foliage chemistry (FC), Forest Damage (FD)
F1 spruce	20	815	0.045	Microbial decomposition (MB), Soil chemistry (SC)
	30	815	0.21	Throughfall (TF), Soil water chemistry (SW), Litterfall chemistry (LF)
	50	815	0.25	Tree bioelements (BI), Vegetation (VS)
	70	815		Foliage chemistry (FC)
F4 spruce	10	787	0.04	Throughfall (TF)
				Hydrobiology of streams (RB)

closed to open and subsequently again to heterogeneously closed, by numerous young regenerating spruce especially. The spruce stand F4 remained healthy (2011: 1100 $m^3.ha^{-1}$).

Throughfall – 15 (B1, F1) and 10 (F4) buckets of 320 cm^2 openings are used to collect throughfall in weakly intervals. Samples are measured for pH and electric conductivity to check for contamination, combined to one sample for each week and filtered (0.45 µm, Whatmann) prior to analysis.

Soil water – Organic layer leachate is captured by six (B1 and F1) zero-tension lysimeters, which are emptied weekly and combined to biweekly volume weighted samples. For mineral soil leachates in 0 cm, 70 cm, and 100 cm below ground, four suction cup lysimeters in each depth are operated with a suction pressure of 300 hPa, emptied biweekly and combined to monthly volume weighted samples. Monthly samples are prepared for chemical analysis as described above.

Foliage chemistry – Nutrient supply of eight mature trees each (B1 and B2) is estimated by sampling (July/August), drying and analysing green sunlit leaves of the crown periphery for macro elements especially.

Litterfall chemistry – Organic material shed from the canopy is captured by six (B1 and F1) and nine (B2) litter traps (0.25 m^2). Contents are sampled monthly, separated into leaf, reproductive organs and wooden parts, weighed after drying and analysed (see above). To catch larger parts (e.g. twigs and branches), three nets (8 m² each) fixed to ground surface are used.

Microbial decomposition – Since 1994, the loss of dry weight of the litter bags (1 mm mesh size, 2.5 g brown pine needles) fixed to ground surface is measured after one, two, and three years of exposition (B1, B2, and F1, respectively). On the spruce plot, the program had to be finished in 2005 due to problems in accessibility.

Station based programs

Air chemistry and meteorology – The concentrations of SO_2, NO_x and ozone in ambient air and basic meteorological parameters are continuously measured at the top of a 51-m tall measuring tower. At the same height, temperature, relative humidity, wind and insolation are recorded. Record interval is one minute, reporting interval 30 minutes. Further climate data are taken from Große Ohe and NPBW data pool (see above).

Precipitation chemistry – Precipitation is sampled weakly using three buckets of 320 cm² openings. Samples are measured for pH and electric conductivity to check for contamination, combined to one sample for each week, and filtered (0.45 µm, Whatmann) prior to analysis.

Groundwater chemistry – Monthly to bimonthly samples of fresh non-stagnant ground water are taken by using an immersion pump and prepared for chemical analysis as described above.

Runoff water chemistry – In 1990, continuous water level measurements in the Forellenbach stream have launched at the Schachtenau stream gauge (V-notch weir) using a pressure sensor. Independent discharge measurements with a current meter are conducted to check the rating curve. Samples are taken automatically in fixed intervals (30 min) to produce combined daily samples which are tested for pH and electric conductivity. The last sample of each weekly interval (Monday) is prepared for chemical analysis as described above, summing up to 52 analytical data sets a year.

Data availability

Recorded data and metadata are available since 1990 upon request (Excel spreadsheet format) from the Federal Environment Agency (UBA). There are no larger or systematic gaps in data series.

Integrated hydrological monitoring (IHM) in the Markungsgraben catchment[†]

The Markungsgraben subcatchment (see Table 1 and Fig. 1) is 1.1 km² in size and the altitudinal range is from 890 m (the gauge Racheldiensthütte, 48°57'20.89'' N, 13°25'35.8'' E) to 1355 m a.s.l. (Plattenhausenriegel).

The catchment is 99% forested, with Norway spruce (84%) and European beech being the dominant species. It covers predominantly upper slopes and plateau, adjacent to the Forellenbach catchment. Further physiographic and hydrometeorological characteristics are shown in Table 1, the subprograms of IHM and the sampling intervals in Table 3. The location of plots and stations is given in Fig. 1; more detailed information about the sites, parameters, and methods has been published elsewhere (Moritz et al. 1994, Moritz & Bittersohl 2000, Bittersohl et al. 2004).

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Table 3. Subprograms of the Markungsgraben Integrated Hydrological Monitoring (IHM).

Subprogram	Elevation (m a.s.l.)	Measurement	Sampling interval
Precipitation	960	quantity and quality	2 weeks
Throughfall	970	quantity and quality	2 weeks
Soil water	970	quality	4 weeks
Spring water	1010	quality	4 weeks
Groundwater	970	level and quality	8 weeks (summer)
Runoff	890	quantity and quality	2 weeks

Intensive monitoring plot

Throughfall, soil water, and groundwater measurements are performed in a former mature Norway spruce stand (1988: 94%, 412 $m^3.ha^{-1}$) with second and third layer European beech (6%). It died out during 1990 (partly) and 1997 (completely), constituting a mixed regenerating spruce/beech stand (Bittersohl et al. 2004).

Water sampling

Precipitation and throughfall is sampled biweekly using three and 15 buckets of 320 cm^2 openings, respectively. Mineral soil leachate in 50 cm and 200 cm below ground is sampled every four weeks using eight suction cup lysimeters in each depth which are operated with a suction pressure of 300 hPa. Spring water is sampled every four weeks and groundwater four times a year. Runoff water is sampled manually in two week intervals.

Physical measurements

Climate data are taken from the NPBW and Große Ohe data pool, which is also used for groundwater level data. Continuous water level measurements in the Markungsgraben stream are performed at the Racheldiensthütte gauge (Fig. 1) using a pressure sensor. Independent discharge measurements by a salt dilution method are conducted to check the rating curve.

Data availability

Recorded data and metadata are available since 1987 upon request (Excel spreadsheet format) from the Bavarian Environment Agency (LFU). There are no larger or systematic gaps in data series.

Results and discussion

The Große Ohe catchment

Increasing deposition loads of acidifying air pollutants affected soil quality and tree health, as well as water quality and the integrity of hydrobiological communities in the region. Therefore, LFU and UBA selected small nested catchments (Fig. 1) during the late 1980s to launch separate monitoring programs, which focus on transboundary air pollution effects on groundwater quality (IHM) and whole ecosystems (UN ECE-IM). These programs offer the chance to analyse the hydrological cycle in a more sophisticated way, by contributing both physical and chemical data of precipitation, throughfall, soil water, ground water, and runoff water. For example, Haag (1997) applied an End-Member-Mixing-Analysis on all available water chemistry data (1992–1994) firstly to quantify the specific runoff contribution of soils

Table 4. Mean values (± standard deviation) of precipitation, runoff, and catchment balance (≈ evapotranspiration) in the periods before and after the breakpoint, and their differences (in mm.yr^{-1}); P – probability level.

Periods:	1980–1998	1999–2011	Difference	P
Precipitation	1599±233	1651±261	52	0.29
Runoff	956±191	1079±222	123	0.06
Catchment balance	643±81	572±95	–72	0.02

and aquifers in these three catchments and secondly to identify the mechanisms of episodic stream acidification (Haag et al. 2001). Schwarze & Beudert (2007) and Schmitt (2008) used isotopic and chemical tracer to separate hydrographs for identifying and quantifying runoff generation processes. The course of soil water contents in different depths and the recorded changes in ground water level from IHM and UN ECE-IM were successfully used to validate the results of the tracer approach.

Since the early 1990s, recovery of soils and aquatic ecosystems from airborne acidification proceeded (Beudert & Breit 2010), while spruce dieback following bark beetle outbreaks accelerated in the catchment. Therefore, particular attention has been paid to natural disturbance effects on hydrological and biogeochemical processes and element budgets (Nationalpark Bayerischer Wald 1999, Zimmermann et al. 2000). Klöcking et al. (2005, 2007) used the GIS-based, multiscale ArcEgmo-PSCN modelling system for a spatially distributed simulation of hydrological processes. Compared to pre-outbreak conditions, spruce dieback on more than 30% of catchment area resulted in a decrease in interception evaporation (70 mm.yr^{-1}) and transpiration (60 mm.yr^{-1}), while evaporation from soil surface and depressions (60 mm.yr^{-1}) and runoff (70 mm.yr^{-1}) increased. A statistical analysis of the Große Ohe runoff (1980–2011) strongly confirmed these findings (Kaiglová et al. 2015). The time series of runoff coefficients revealed a significant breakpoint in 1998/1999 (Fig. 3, $P<0.03$), when the extent of disturbed area exceeded 30% of the area (Fig. 4). The mean values differed significantly ($P<0.003$) between the before-breakpoint period (59±5%) and the after-breakpoint period (65±5%). In the second period, mean catchment balance, which approximates the mean evapotranspiration in the longer term, was 72 mm lower (11%, $P<0.02$) than in the period before (Table 4). Despite the increased annual runoff, high flow measures did not increase or even decreased, while low flows increased in autumn. Moreover, comparative investigations of regional runoff reveal decreasing annual and summer runoff yields in less disturbed catchments, despite increasing precipitation yields. In the heavily affected catchments (Große Ohe and upper Vydra), however, decreased canopy cover and thus evapotranspiration losses compensate for significant warming effects.

Extended spruce dieback following bark beetle outbreaks raised fears in regional people about negative impacts on fresh water used for drinking water. Indeed, under humid climatic conditions, excess mineralisation and the leaching of nitrate from soils is a consequence of decoupled nutrient cycles after disturbance (Vitousek 1979, Mikkelson 2013). The monitoring programs in the Große Ohe catchment allowed for addressing that problem: the Große Ohe runoff water represents streams feeding large regional reservoirs, whereas runoff and ground waters of the nested Forellenbach and Markungsgraben subcatchment represent water supplies directly used by local municipalities.

For five years after the complete die off of the mature spruce stand, nitrate concentration in seepage water reached almost 200 mg.l^{-1} in upper mineral soil (Fig. 4), but came back to pre-disturbance values of <10 mg.l^{-1} after six years (Dieffenbach-Fries & Beudert 2007). Groundwater in monitoring boreholes never exceeded 30 mg.l^{-1} (Beudert et al. 2015, Fig. 4).

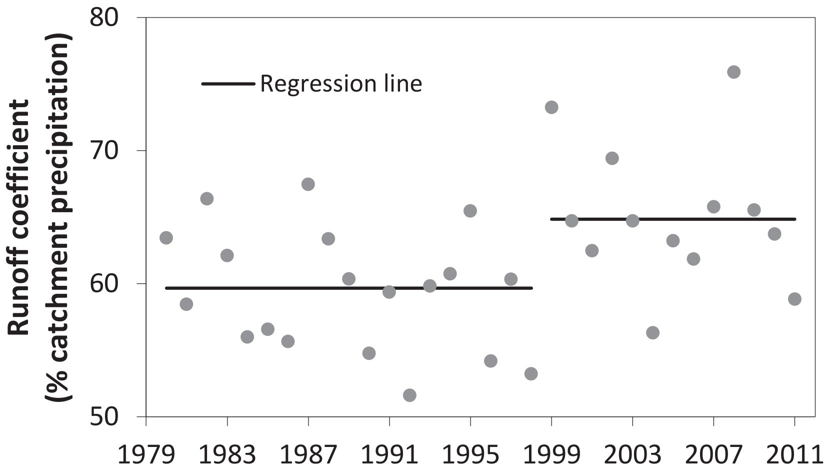

Fig. 3. Annual runoff coefficient (percentage catchment precipitation) in the Große Ohe catchment (Kaiglová et al. 2015). It shows a significant breakpoint (P<0.03) in the time series in 1998/1999.

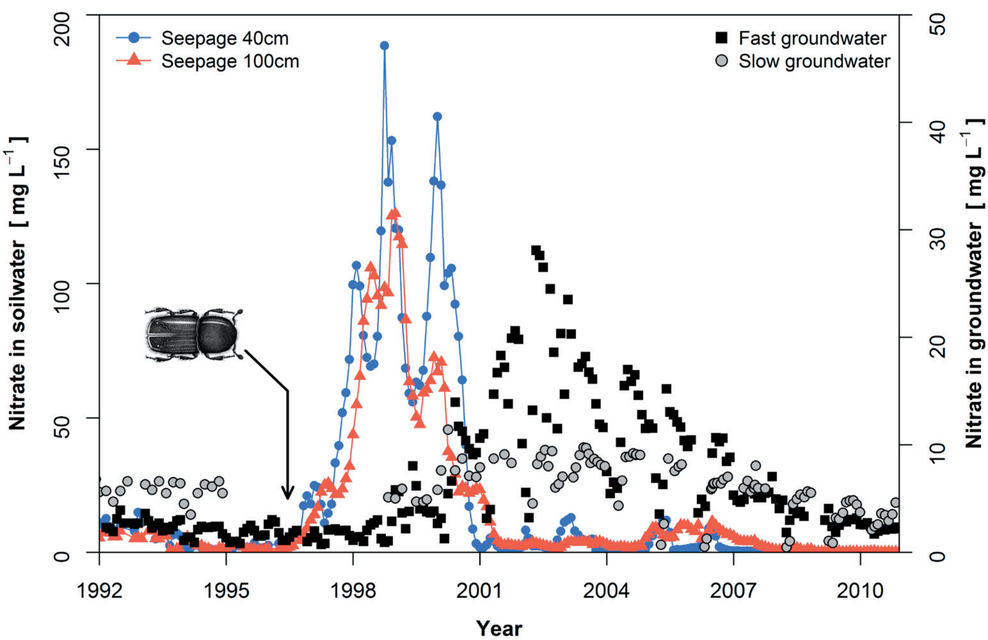

Fig. 4. Nitrate concentrations in seepage water and groundwater. Volume-weighted monthly means of nitrate concentrations in seepage water in 40 cm and 100 cm of the Norway spruce stand (Forellenbach) are displayed on the left axis, nitrate concentrations of fast (Forellenbach) and slow flowing groundwater (Markungsgraben) on the right axis. The spruce stand completely died after bark beetle infestation in June 1996 (modified from Beudert et al. 2015).

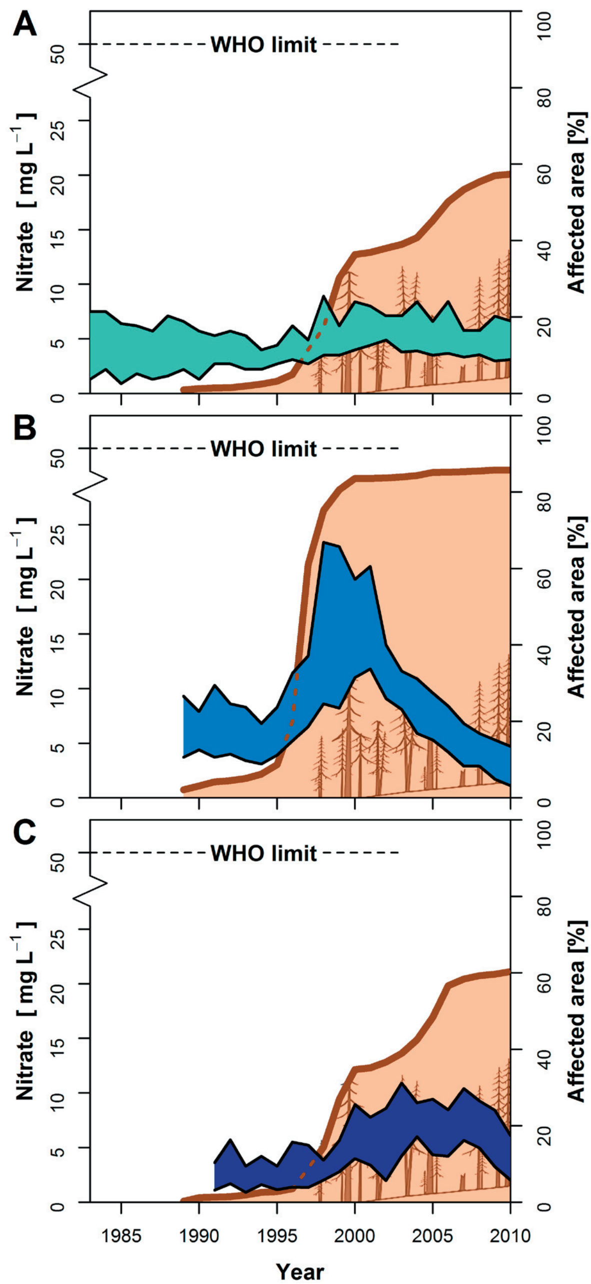

Fig. 5. Times series of bark beetle-affected areas and nitrate concentrations. Brown coloured areas represent cumulative percentages of bark beetle-affected areas of each catchment, while blue coloured areas indicate the respective annual ranges of nitrate concentrations in runoff water. The World Health Organization (WHO) drinking water guideline limit is 50 mg.l^{-1}. A: Große Ohe catchment; B: Markungsgraben subcatchment; C: Forellenbach subcatchment (Beudert et al. 2015).

Nitrate concentrations remained <30 mg.l^{-1} throughout in weekly to biweekly sampled stream water of the Große Ohe catchment and its nested Forellenbach and Markungsgraben catchments, even though the disturbed area reached 57%, 58% and 80% of the catchments, respectively (Fig. 5). Across hydrological pathways, mixing of nitrate-rich soil and hypodermic water from the disturbed areas with nitrate-poor soil water from undisturbed areas and ground water exerts control over stream nitrate concentration. As slow-flowing ground water exhibits a mean residence time of 8 to 15 years (Klöcking et al. 2005), high ground water contribution of 50% to 80% to runoff (Beudert et al. 2007) places an effective ceiling on nitrate concentrations. In any stream, ground water, official spring tapping, or reservoir, the usability of freshwater for drinking water purposes (World Health Organisation guideline for nitrate: 50 mg.l^{-1}) has never been affected.

The Forellenbach catchment

In the Forellenbach area, atmospheric deposition of sulphur decreased substantially by about 70% and 80% (during 1992–2013) under beech and spruce, respectively. Consequently, since the input of dissolved inorganic nitrogen (DIN) decreased only little and the input of base cations remained unchanged, acid neutralising capacity (ANC) increased stoichiometrically.

Soil solutions under beech B1 (40 cm and 100 cm, Fig. 6) responded significantly with decreasing (> 50%) concentrations of sulphate (SO_4^{2-}), aluminium (Al^{n+}) and free acidity

Fig. 6. Intensive monitoring plot in beech stand B1 (Forellenbach) with precipitation gauge and buckets, rain gutter, snow gauge, and litter traps (photo: W. Breit 2015).

(H^+), and with increasing ANC. Base cations and nitrate (NO_3^-) decreased as well, indicating enhanced nutrient uptake by the trees. In regenerating spruce stand F1, recovery from airborne acidity was counteracted by excess mineralisation (formation of nitric acid), which followed the bark beetle induced dieback (1996/1997) of the old growth stand. Between 1997 and 2001, NO_3^- increased by one order of magnitude in maximum, with Al^{n+} being almost stoichiometrically controlled by NO_3^- (Beudert 1999). Before and after that period, Al^{n+} correlated significantly with SO_4^{2-} in mineral soil solutions.

Changes in stream water chemistry documented the recovery of mineral top soils from acidification (Beudert & Breit 2011). The minimum pH during high flood events increased substantially from 4.5 to 5.5, which resulted in decreasing activities of hazardous aluminium species. The concentrations of Al^{n+}, Fe^{n+}, H^+, and dissolved organic carbon (DOC, Fig. 7) showed a significant positive correlation with log discharge and among each other, thereby identifying organic layer (i.e. DOC) in contact with mineral top soil (Al^{n+}, Fe^{n+}) as hot space and source of acidifying compounds during high flow. Until 2004, SO_4^{2-} significantly correlated positively with log discharge and Al^{n+}, but regression coefficients also decreased significantly (Fig. 7). NO_3^- contributed to episodic stream acidification for two years only. Since 2005, SO_4^{2-} has lost all relevance to episodic acidification, indicating that in the Forellenbach catchment the recovery from anthropogenic airborne soil acidification is mostly completed. DOC now plays the decisive role in controlling pH during high flood events. Apart from possible effects of climate change on DOC production and/or quality, episodic stream acidification by DOC has to be considered as a natural process (Beudert & Breit 2011).

Already in the 1990s, but more pronounced in the study period from 2003 to 2012, mean input of dissolved inorganic nitrogen (DIN) under beech and spruce canopy was about 10 $kg.ha^{-1}.yr^{-1}$ and almost equalled input via bulk precipitation (Fig. 8). Such small differences obscure possible contributions of dry deposition and physical, as well as biological, exchange and transformation processes in the canopy. Dissolved organic nitrogen (DON) amounted to 7% (bulk precipitation) and 27% (throughfall on spruce plot) of measured total nitrogen input (TNb), indicating biological interactions.

The site specific critical loads of reactive, eutrifying nitrogen for local forest ecosystems range from 10 to 15 $kg.ha^{-1}.yr^{-1}$ (Beudert & Breit 2004) which is identical to empirical critical loads for all receptor groups in these forest types (Bobbink & Hetteling 2011). The crucial point, however, is to accurately determine the total deposition of reactive nitrogen with respect to critical load exceedance and possible harmful effects on ecosystem functioning and services. Beudert & Breit (2014) tested a couple of canopy budget models to derive total deposition estimates for the period 2003–2012. Small sodium based dry deposition factors of 0.14 and 0.19 for beech plot B1 and spruce plot F4, respectively, revealed small amounts of particle deposition rates indicating the remoteness of this area. Model averages (2003–2012) of total DIN deposition were in the range of 10–13 $kg.ha^{-1}.yr^{-1}$ on the beech plot B1 and 11–17 $kg.ha^{-1}.yr^{-1}$ on the healthy spruce plot F4, whereas the maximum model results were 15 $kg.ha^{-1}.yr^{-1}$ (B1) and 22 $kg.ha^{-1}.yr^{-1}$ (F4).

Maximum DIN retention rates from canopy budget models, ranging from 3 $kg.ha^{-1}.yr^{-1}$ (beech B1) to 7 $kg.ha^{-1}.yr^{-1}$ (spruce F4), seem to be plausible when nitrogen uptake by the very abundant epiphytic lichens and microorganisms is taken into account, in addition to the uptake by tree leaves, adsorption on stand surfaces, and biochemical transformations.

In summary, the mean (2003–2012) modelled total DIN deposition of 11 $kg.ha^{-1}.yr^{-1}$ on the beech plot B1 and 12 $kg.ha^{-1}.yr^{-1}$ on the spruce plot F4 equalled the sum of DIN throughfall and net DON throughfall (throughfall minus precipitation) on each plot. As it includes possible biological DIN sinks not accounted for in the models, the sum of modelled total DIN

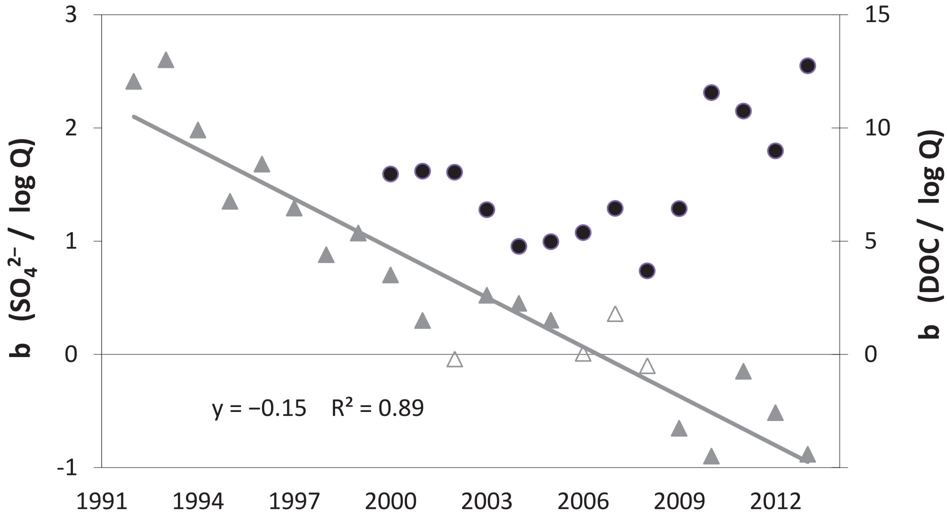

Fig. 7. Annual regression coefficients of concentration (mg.l^{-1}) versus log discharge (l.s^{-1}) relations of Forellenbach stream water samples (n≥52 per year). Left ordinate and triangles: sulphate (SO_4^{2-}); right ordinate and circles: dissolved organic carbon (DOC); filled symbols indicate statistical significance ($P<0.05$). Until 2005, the sulphate concentration increased when discharge increased, indicating higher sulphate concentration in mineral soil water than in groundwater. Since 2009, the sulphate concentration is decreasing when the contribution of soil water to runoff is increasing. Episodic stream acidification is now due to natural organic acids (DOC) only.

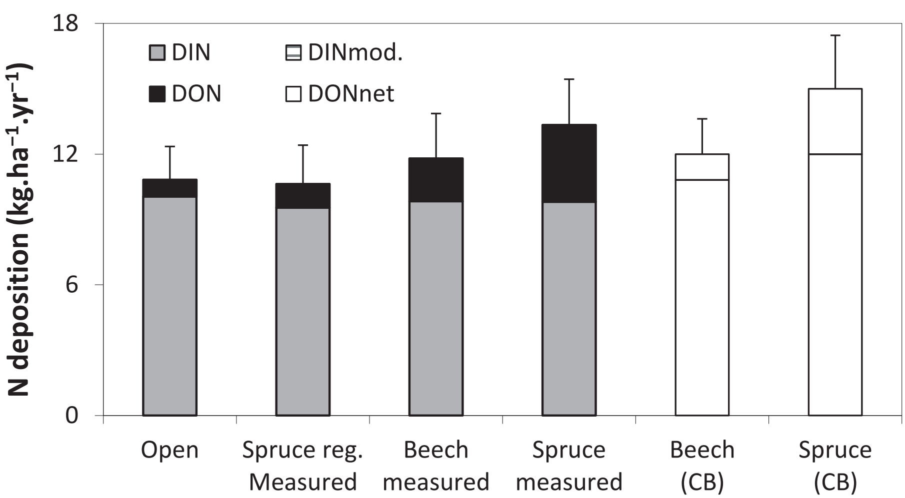

Fig. 8. Mean nitrogen deposition in the Forellenbach catchment (2003–2012). Measured deposition of dissolved inorganic (DIN) and organic nitrogen (DON) in beech plot B1 and spruce plot F4 is compared with (i) measured deposition at open site and in regenerating spruce stand F1, and (ii) total nitrogen deposition from application of canopy budget models (DINmod.) plus net throughfall of dissolved organic nitrogen (DONnet) in these stands. Note that error bars display one standard deviation of the sum of components at each site.

deposition and net DON throughfall of 12 kg.ha^{-1}.yr^{-1} (B1) and 15 kg.ha^{-1}.yr^{-1} (F4) has been proposed as a robust estimate of total DIN deposition in the lower elevation tree stands of the Forellenbach catchment (Beudert & Breit 2014). This is in accordance with the modelled total DIN deposition of 14 kg.ha^{-1}.yr^{-1} (2002–2011) reported for regional EMEP grid 71/48 (http://webdab.emep.int/Unified_Model_Results/).

Between 1st September and 5th December 2011, measurements of atmospheric deposition focussing on reactive nitrogen were performed in the summit region of the Bavarian Forest National Park (Beudert & Breit 2012). In addition to wet deposition (open site) and throughfall measurements, a fog and cloud water sampler was installed at Mt. Großer Falkenstein (1315 m a.s.l.). The combination of these approaches was expected to give insight into the quality and quantity of compounds due to the interception of water droplets, which is called moist or horizontal deposition.

The throughfall amount varied between 380 mm to 735 mm in this period and was about 53% and 197% higher than precipitation in this comparatively dry autumn, indicating a high net gain by horizontal water interception. In contrast, the low elevation stand in the Forellenbach catchment lost 35% of precipitation by evaporation of intercepted water. Open site deposition of measured total nitrogen (TNb) was 1.0 kg.ha^{-1} at the low elevation site (762 m a.s.l.) and 1.2 kg.ha^{-1} at the high elevation site, reflecting mostly the difference in precipitation amount. At low elevation (782 m a.s.l.), periodical input via throughfall was 2.3 kg.ha^{-1}, but increased up to 10 kg.ha^{-1} at Mt. Großer Falkenstein.

Cloud and fog water was sampled with a cylindrical harp, stringed with Teflon strands, during 15 intervals of mostly one day duration each. Four of these sampling days were classified as rich in precipitation (>3.9 mm), four of them as poor in precipitation (<3.9 mm), and seven intervals were completely free of rain. For distinguishing purposes, water from intervals with rain >3.9 mm was labelled "cloud water", while water from other intervals was labelled "fog water", suggesting that there was a marked difference in large droplet contribution. Cloud water offered median concentrations of 2.3 mg.l^{-1} TNb, 1.1 mg.l^{-1} NH_4-N, and 0.9 mg.l^{-1} NO_3-N, and variability was low. In contrast, median fog water concentrations were several times higher with 7.3 mg.l^{-1} TNb, 4.1 mg.l^{-1} NH_4-N, and 4.3 mg.l^{-1} NO_3-N, but variability was very high (Fig. 9). Maximum concentrations in cloud water did not exceed minimum concentrations in fog water. Only fog water was able to reproduce most of high N concentrations in throughfall in this period, with the exception of a few sampling intervals in November. They could be traced back to the dry deposition of NO_X, which were enriched near the ground surface during inversions and transferred to high elevation spruce stands as atmospheric stratification returned to normal conditions.

In summary, the contribution of precipitation to the deposition of air pollutants at the top of Mt. Großer Falkenstein was comparatively small and very similar to that of the low elevation site in the Forellenbach catchment. The moist deposition, however, the interception and dripping of droplets in the spruce canopy, together with dry deposition of gases and particles, was of overriding importance for the nitrogen load of spruce ecosystems.

The Markungsgraben catchment

From 1989 to 1991, shortly after the emission of acidifying gases (most prominently SO_2 from combustion processes), the mean sulphate concentration in precipitation and throughfall was about 4.2 mg.l^{-1} and 10.3 mg.l^{-1} (Fig. 10) illustrating the filtering effect of Norway spruce canopies. Sulphate concentration in soil water at 50 cm and 200 cm was 10.1 and 9.4 mg.l^{-1}, indicating equilibrium between sulphur input and storage in mineral soil. In groundwater (long-term mean level is about 10 metres below ground) and runoff, however, mean concentration was 4.9 mg.l^{-1} and 4.1 mg.l^{-1} only. This suggests large sorption capacities in

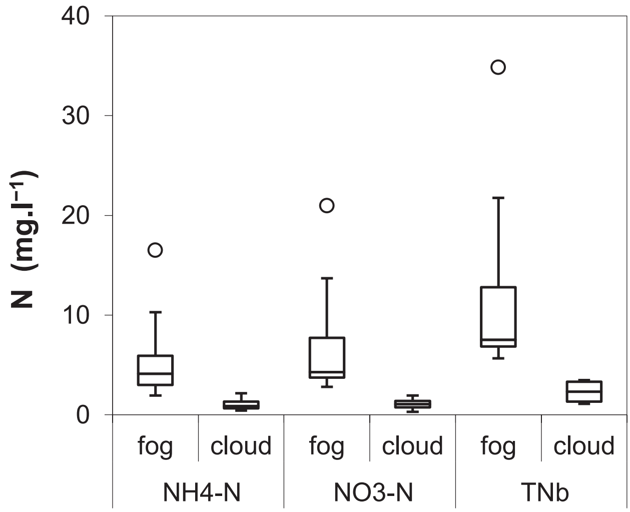

Fig. 9. Box plots of nitrogen concentration in mostly daily samples of fog and cloud water captured by a cylindrical harp at Mt. Großer Falkenstein (1315 m a.s.l.) between 1st September and 5th December 2011. A precipitation amount of 3.9 mm per sampling day was found to differentiate between "cloud" (>) and "fog" (<) water. Note that the nitrogen concentrations in throughfall samples are generally higher than those in cloud water of the same intervals.

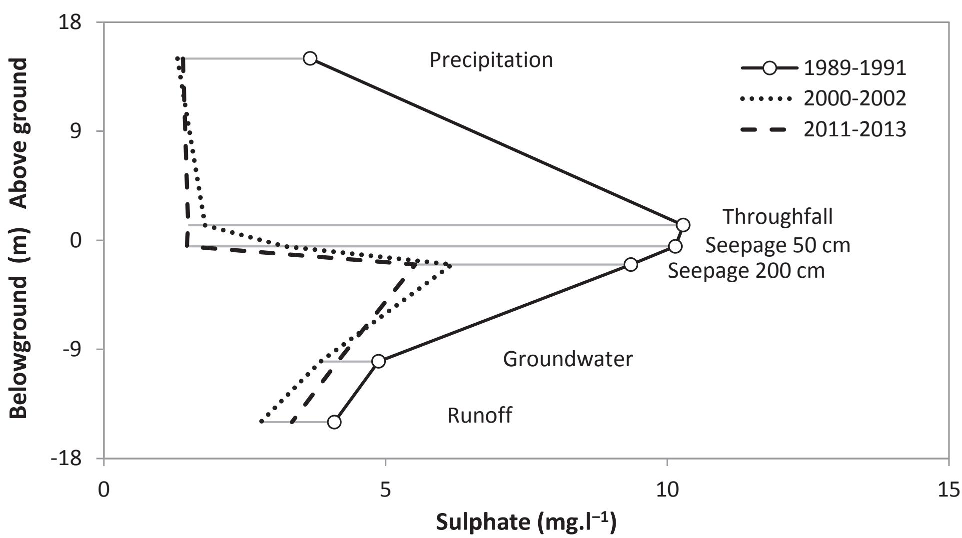

Fig. 10. Mean concentration of sulphate (mg.l^{-1}) in precipitation, throughfall, and soil waters on intensive monitoring plot as well as in groundwater and runoff of the Markungsgraben catchment. Concentrations are averages over three-year periods in each compartment; light grey lines illustrate the difference between the highest and lowest concentration in each compartment.

the regolith above fissured bedrock. Already ten years later (2000–2002), sulphate concentrations had decreased by two thirds in precipitation and by 80%, 70% and 66% in throughfall, seepage water in 50 cm and in 200 cm depths, respectively. About 20 years later (2011–2013), sulphate in open site and stand precipitation as well as in deep seepage, ground water and runoff showed no further significant decrease. In contrast, sulphate in seepage water in 50 cm depth halved again to about one fourth of the concentration in the deeper seepage water, whereas it had equalled at the beginning of the data series. These results from the Markungsgraben catchment strongly confirm earlier investigations (Haag et al. 1999) and recent findings from the Forellenbach catchment (Beudert & Breit 2011), that episodic acidification of stream water is no longer due to sulphate input via soil water. However, the process of soil recovery by sulphate desorption has been proceeding top down, in reversal of the former acidification progress, but will take further decades to be finished in the whole hydrogeological system (Bittersohl et al. 2014).

Since the beginning of hydrological monitoring in the Markungsgraben catchment, nitrogen deposition has been decreasing by 22% at open site (Fig. 11), i.e. much less than sulphur deposition. The decrease in throughfall (38%) is partly due to the loss of canopy after the spruce dieback by bark beetle infestation and its subsequent change in canopy cover (species, closure). The dieback and its consequences in element cycling (see Fig. 4) is reflected by high mean concentrations of dissolved inorganic nitrogen (DIN) of 4.9 and 4.2 mg.l^{-1} (about 22 and 18 mg.l^{-1} nitrate) in seepage water in 50 cm and 200 cm depth respectively. In recent years (2011–2013), DIN concentration is <0.1 mg.l^{-1} (0.4 mg.l^{-1} nitrate) indicating efficient and almost complete uptake of inorganic nitrogen by plants and microorganisms on this plot.

From 1989 to 1991, DIN concentrations in groundwater and runoff were much lower than in soil water as, at that time, bark beetle damages accounted for less than 2% of the catch-

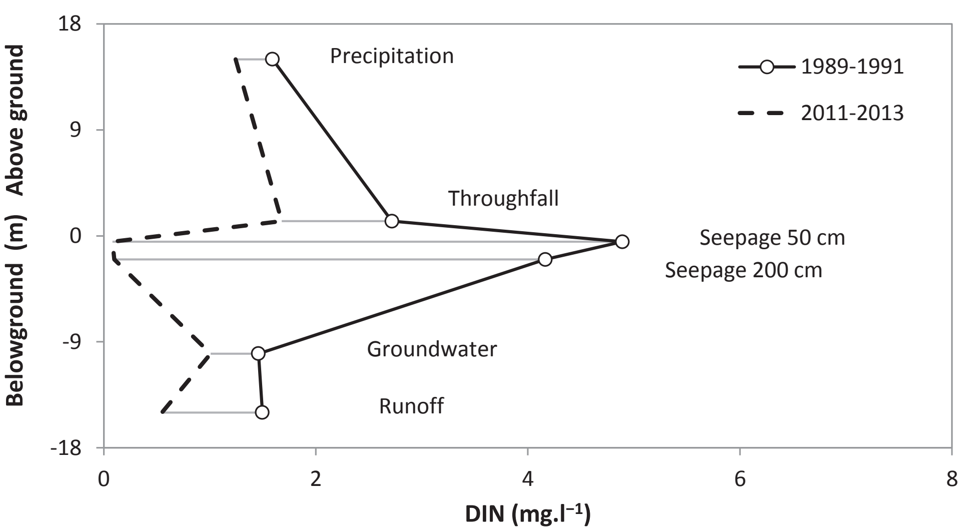

Fig. 11. Mean concentration of dissolved inorganic nitrogen (DIN, mg.l^{-1}) in precipitation, throughfall, and soil water on intensive monitoring plot, as well as in groundwater and runoff of the Markungsgraben catchment. Note that in subsurface and runoff waters, ammonium concentration typically approaches zero, while nitrate represents DIN by almost 100%. Concentrations are averages over three-year periods in each compartment; light grey lines illustrate the difference between the highest and lowest concentration in each compartment.

ment area (Fig. 5). Twenty years later, when the bark beetle killed mature spruce stands on more than 80% of the catchment area and nitrate intermediately increased to about 23 $mg.l^{-1}$ in maximum (Fig. 5), DIN concentrations in groundwater and runoff are even lower than at the beginning. This is the result of large nitrogen losses during (1995 to 2000) and after the dieback (until 2005) and the depletion of readily biodegradable organic nitrogen (Beudert et al. 2015) in the whole catchment.

Conclusions

The foundation of the Bavarian Forest National Park and the implementation of the Große Ohe catchment for "the investigation of changes … during and due to the transition from commercial to near-natural forest without management intervention" has been a wise and far-sighted decision. We can only speculate whether or not these decisions would have been made given the extended bark beetle outbreaks and storm disaster occurring during the last decades. But without them, we would have to speculate about ecosystem behaviour during and after disturbances and about possible impacts on basic ecosystem services. So we are grateful to have this unique real-world data set as a basis for further scientific efforts, which also helps to improve the scientific advice of nature management and conservation policy. Future investigations will focus on the causes for the non-synchronous increase of dissolved organic carbon concentration in different freshwater systems of the Große Ohe catchment (Beudert et al. 2012) and the fluxes of total reactive nitrogen over forest (Ammann et al. 2012, Brümmer et al. 2013).

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Appendix I: Relevant papers out of the monitoring programs in the Große Ohe catchment**.**

Peer-reviewed papers:

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