| Silva Gabreta | vol. 4 | p. 51–62 | Vimperk, 2000 |
| --- | --- | --- | --- |

# Influence of bark beetle infestation on water quantity and quality in the Grosse Ohe catchment (Bavarian Forest National Park)

**Lothar Zimmermann[1], Klaus Moritz[2], Martin Kennel[1] & Jochen Bittersohl[2]**

[1]*Bavarian State Institute of Forestry (LWF), Am Hochanger 11, D–85354 Freising, Germany*
[2] *Bavarian State Office for Water Management, Lazarettstraße 67, D–80636 München, Germany*

**Abstract**

Since 1995 infestation by spruce bark beetle has caused up to 75 % forest die-off in the highland area of the eastern Bavarian Forest National Park stocked with Norway spruce. Proportional to infested areas effects on water quantity and quality can be studied at catchment scale. The strongest effects can be seen in the "Markungsgraben" catchment (1999: 81% of the forested area died off). Beside increasing discharge, water quality is strongly influenced by forest die-off. In seepage water nitrate concentrations partly exceeded 50 mg/l, while in stream and spring water maxima around 25 mg/l were reached. Ground water in a depth of 5–10 m in the "Markungsgraben" catchment as well as the stream water of the "Grosse Ohe" (1999: 30 % of the forested area died off) show up to the present no distinct reaction. Taking into account that about 40 % of the remaining forested slope area is endangered the question arises about the future development of water quality. An annual based nitrogen budget model enables conclusions about future nitrogen release. A worst-case scenario with complete forest die-off on the slopes and no uptake by ground vegetation predicted nitrate concentrations in stream water only temporarily reaching 40 mg/l.

*Key words:* bark beetle mass propagation, water budget, water quality, *Ips typographus*.

## Introduction

Since 1995 mass propagation of the engraver bark beetle (*Ips typographus*) started in the inner Bavarian Forest due to preceding blow-downs and favourable climatic conditions (dry and warm summers) (Nuesslein & Faisst 1998). According to the aim of the Bavarian Forest National Park, "leaving nature alone", natural processes were given absolute priority so no counter-measures against the bark beetle infestation were undertaken in the south-eastern part of the National Park (Rachel-Lusen area) except for a border zone of 500–1000 m to prevent further spreading. In the inner zone the dead trees were left standing to natural decay without any disturbance. Especially in the park highlands the extended die-off of spruce reached 75% of the original forested area in fall 1999 (Nuesslein & al. 2000). This has effects on the water and element budgets of the forest ecosystem comparable to large-scale blow-downs or clear-cuts (Vitousek & Mellio 1979). Characteristic features of such events are the loss of the stand structure, the abrupt increase in dead biomass in contrast to the former continuous process of litterfall and the strong decrease in water and nutrient uptake by the death of fine roots. Beside this decrease of transpiration needle loss reduces interception loss. This decrease in evapotranspiration leads to an increase in soil moisture, ground water recharge and discharge. A review of 96 North American catchment experiments found a critical value of 20–30% deforestation before reactions in discharge could be noted (STEDNICK 1996). Highland catchments were especially sensitive to deforestation and showed prolonged reaction due to slower vegetation regrowth. Due to the marked decrease in scavenging efficiency through defoliation the deposition of fog, aerosols and gases is reduced, so that the total atmospheric input to the forest ecosystem decreases. This loss in fog interception or so-called occult precipitation compensates partly the loss of interception in the evapotranspiration term. Yet measurements with passive fog collectors at the Grosse Falkenstein summit in the Bavarian Forest (BAUMGARTNER 1958) as well as results from a fog deposition study at various German hill sites in the 90s (PAHL 1996) show that fog deposition decreases exponentially with altitude, so that with increasing catchment size the proportion of lower situated areas increases and this compensation looses importance. Due to enhanced insolation soil temperature rises which in combination with the increased moisture leads to an accelerated decomposition and mineralisation of the dead biomass. Since nutrient uptake of the stand ceases, nitrate release and percolation increases in the first years after the disturbance until the upcoming secondary vegetation partly compensates. This "excess nitrification" leads to an increased aciditiy production, which is buffered by alkaline cations or aluminium from the soil exchanger depending on the site-specific base state. According to the concept of electro-neutrality these cations accompany the mobile anion nitrate and are leached from the soil. These effects have special importance in view of the now slowly decreasing acidification of ecosystems caused by long-term high sulfur loads. pH-depressions and increased levels of aluminium endanger river ecosystems, especially fish. In addition costs for drinking water purification are increasing. In case of nitrate (maximum contaminant level for drinking water: 50 mg/l $NO_3^-$) expensive additional techniques for elimination of nitrate or finding suitable other sources for dilution would be necessary. In the passionate public discussion how to manage the bark beetle in the National Park effects of spruce die-off on water quantity and quality gain more and more public interest. The question arises which effects can be seen now and which further development is likely. For answering this question the "Grosse Ohe" benchmark catchment is especially suited, since a long observation period prior to the infestation exists (BRAUN & al. 1999).

## Site Description

The "Grosse Ohe" catchment (Fig. 1) is 19.1 km$^2$ in size and stretches between 770 m a.s.l. (gauge Taferlruck) and 1453 m a.s.l. (Rachel peak). Within the catchment two subcatchments ("Markungsgraben", "Forellenbach") (Fig. 1) are monitored. The 110 ha large "Markungsgraben" catchment represents highlands and upslope areas (890–1355 m a.s.l.), while the 69 ha large "Forellenbach" catchment is mainly representative for the lower valley regions of the "Grosse Ohe" below 900 m a.s.l.. The climate is characterized by high annual precipitation (1630 mm/y) with a high snow proportion (30–40%) and a low annual mean air temperature (5.6 °C). The catchment is nearly totally forested, with deciduous trees (mainly European beech) on 28% of the area while 70% are stocked by conifers (mainly Norway spruce). Soils of the silicate series, predominantly acidic brown earths, have formed on periglacial weathering material derived from gneiss and granite. The highlands differ from slopes and valleys with respect to site conditions. The highlands at the uppermost part of the National Park form a plain and are vegetated by the typical highland spruce forest (*Soldanello-Piceetum barbilophoietosum*) (ELLING & al. 1987). The transition to the slope region is between 1100–1250 m a.s.l..

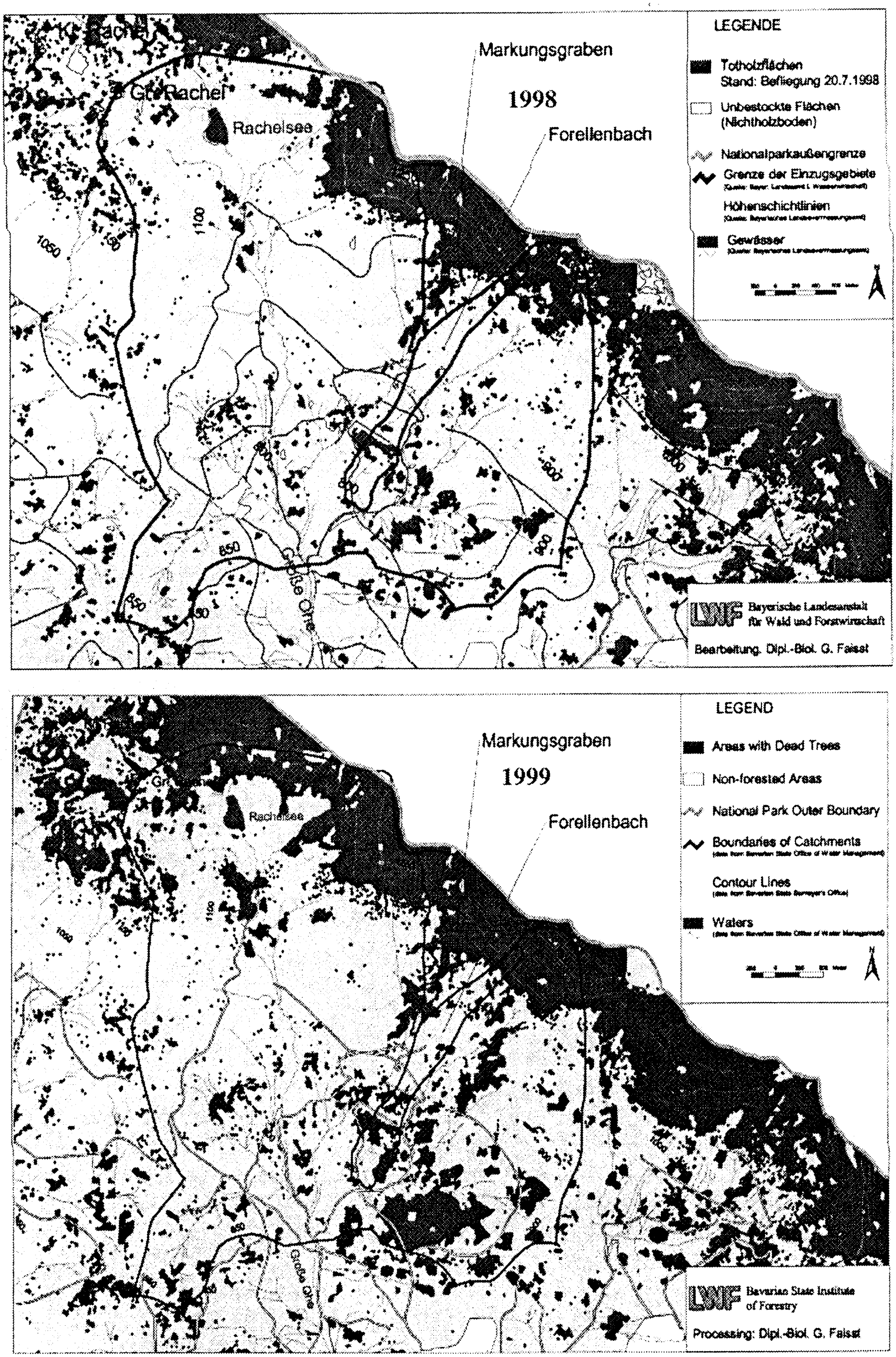


**Fig. 1.** – Patterns of forest die-off in the catchment "Grosse Ohe" and the subcatchments "Markungsgraben" and "Forellenbach" (situation 1998 and fall 1999).

## Methods

Precipitation is monitored within the "Grosse Ohe" catchment by eight totalisators supplemented by three bulk samplers run in the subcatchments "Markungsgraben" (MORITZ & BITTERSOHL 2000) and "Forellenbach" each (BEUDERT & KANTOR 1999). For the "Grosse Ohe" catchment and the "Markungsgraben" subcatchment areal precipitation was calculated as weighted means by the Thiessen polygon method. For the "Forellenbach" catchment areal precipitation was taken from IBK (2000) according to the linear interpolation approach proposed by BEUDERT (IBK 1998). Deposition in the subcatchment "Markungsgraben" is monitored by open-field and throughfall collectors described in MORITZ & BITTERSOHL (2000).

Runoff of the "Grosse Ohe" catchment is recorded by a triangular weir while there is a rectangular weir with a provisional Venturi channel in the „Markungsgraben" subcatchment (MORITZ & al. 1994). At both weirs water levels are measured by a pneumatic gauge run by the Bavarian Water Management Administration. At the V-notch weir of the subcatchment "Forellenbach" water levels are recorded by a conductivity gauge and a standard float-recorder (BEUDERT & KANTOR 1999, BEUDERT 1997). At all three weirs water samples for chemical analysis are taken at fortnightly intervals (MORITZ & al. 1994). Hydrochemistry and depth of ground water are monitored twice a month at a monitoring well which is located in a mature spruce stand (F1) in an up-slope position of the „Markungsgraben" catchment at 970 m a.s.l.. Soil solution is sampled by ceramic suction cups in three depths (50, 100, 150 cm) at F1. Sampling suction is –300 hPa (MORITZ & al. 1994). Methods and quality control for chemical analysis of the water samples are described in HAAG (1997) and MORITZ & al. (1994).

Meteorological standard data were available from the weather station Waldhäuser (945 m a.s.l.) operated by the German Weather Service and the National Park Administration, about two km south-east of the "Grosse Ohe" catchment in a south-westerly oriented slope position and lying approximately in a mid-position in relation to the altitudinal range of the catchment (KENNEL 1998). Measured and derived quantities for global radiation, maximum and minimum temperature, vapour pressure and wind speed were used for the calculation of evapotranspiration in the parameter-lumped water budget model BROOK90 (FEDERER 1997).

The spreading of die-back due to bark beetle infestation was monitored through analysis of aerial photographs which were taken once a year in early summer (except for 1999 with a second flight in October to get an actual picture of large-scale distribution) (NUESSLEIN & al. 2000).

## Results and Discussion

### Spreading of the Bark Beetle Infestation

The spreading of spruce die-off after bark beetle infestation in the Rachel-Lusen part of the National Park was almost identical with the development in the catchments "Grosse Ohe" and "Forellenbach" (Fig. 2), so that these catchments can be taken as representative sections. From 1993 to 1999 the proportion increased from 1 % to 30 %, and from 1% to 27% for the "Forellenbach" catchment, respectively. In contrast, the "Markungsgraben" catchment mirrors the dramatic development in the highlands (1993: 5%, 1999: 81%). In the beginning the bark beetle infested trees were predominantly found in the highlands. Since 1997 the mass propagation increasingly seized spruce stands in the slope and valley region. Until 1998 the infestation formed a patchwork of small areas. Since then larger areas have developed in these regions (NUESSLEIN & al. 2000). This phenomenon can also be seen in the "Grosse Ohe" catchment, where south of the "Forellenbach" a new complex of bark beetle infested area in

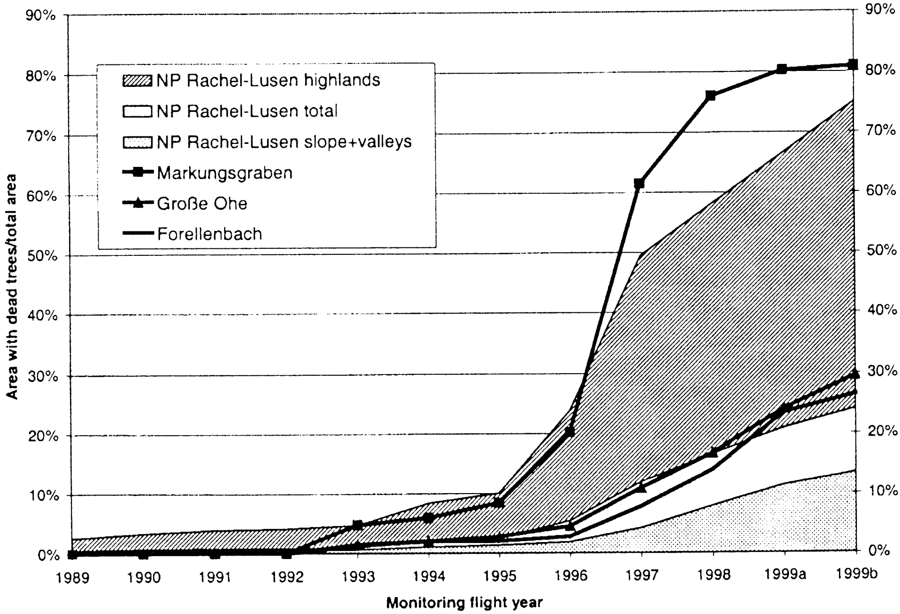


**Fig. 2.** – Development of areas with dead trees within the old national park, its highland and slope region, "Grosse Ohe" catchment and subcatchments "Markungsgraben" and "Forellenbach" (1999: two flights 4.7. and 18.10.).

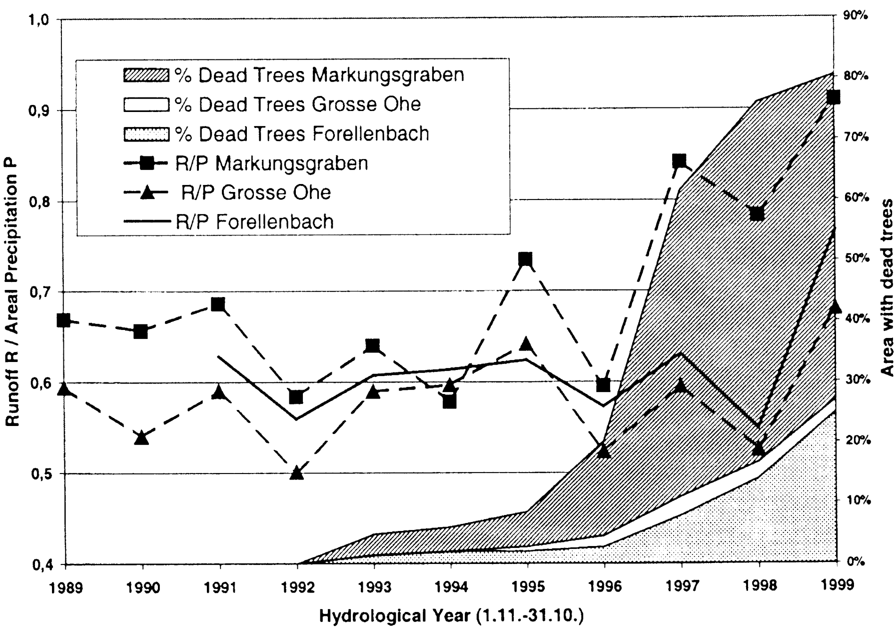


**Fig. 3.** – Annual runoff coefficient (runoff/precipitation) in comparison to areal development of dead trees in the catchments "Markungsgraben", "Forellenbach" and "Grosse Ohe".

the valley position has developed in 1999 (Fig. 1). Spreading of the bark beetle occurred through a corridor-like advancement through mixed stands on the slopes starting from the highlands. Based on stand age (>30 years) and proportion of deciduous trees within the stand 31% of the forested nature zone (area without counter-measures) are assessed to be endangered and further 10% have a limited risk to be infested by the bark beetle (NUESSLEIN & al. 2000).

## Impact on the Water Budget

In all three catchments an increase in discharge is observed now (Fig. 3). Since 1997 the most severely hit highland catchment "Markungsgraben" showed a markedly high runoff coefficient (average 1997–1999: 0.84 compared to 1989–1996: 0.64). In the hydrological year 1999 the runoff coefficients of the two other catchments also exceeded their normal range. It seems that in the Bavarian Forest around 25% deforestation is also a trigger value for discharge reaction as mentioned above.

This reduction in evapotranspiration for the "Markungsgraben" catchment can also be illustrated when comparing evapotranspiration simulated by the water budget model BROOK90 (FEDERER 1997) with the residual term of the measured water budget (areal precipitation (P) minus runoff (R)) as an indicator for evapotranspiration (Fig. 4). In the model run no die-off of spruce is assumed, thus simulating undisturbed conditions. If longer periods of the residuals are observed, the effects of year-to-year storage changes cancel out and the average residual can be regarded as areal evapotranspiration. The eight-year average residual during the undisturbed period (1989–1996: P-R = 597 mm/y) fits quite well the BROOK90 evapotranspiration (1989–1996: ET = 568 mm/y). For the "Grosse Ohe" catchment an average evapotranspiration for the years 1980–89 of 595 mm/y was found by the long-term residual (THUMS 1991). Thus the modelled magnitude appears to be reasonable. In the years 1989–1996 the residuals showed non-systematic fluctuations around the modelled evapotranspiration due to different directions of storage changes each year. In the hydrological years 1997 and 1998 the residuals showed a marked decrease compared with former values and with the modelled evapotranspiration.

A decrease of element deposition in the highland catchment "Markungsgraben" was observed in 1997 and 1998 after the bark-beetle infestation (MORITZ & BITTERSOHL 2000). This confirms the loss of interception capacity seen as well above by the reduction in evapotranspiration.

## Impact on Water Quality

Water quality is influenced by die-off processes as well. For the "Grosse Ohe" catchment information is given on seepage, spring and ground water as well as on stream water. Seepage concentrations are monitored at site F1. At this site vertical percolation towards ground water occurs only episodically. During the wet season interflow predominates (HAAG 1997). Starting in 1989 the reference trees died on the monitoring plot. Since then nitrate concentrations in the soil solution in 50 and 100 cm depth peaked up to 60 mg/l and up to 40 mg/l in 1.5 m depth (Fig. 5). Elevated nitrate concentrations were observed for about four years with peak values one to two years after the die-off. Afterwards increasing development of ground vegetation consuming nitrogen and weakening excess nitrification resulted in decreasing concentrations down to less than 10 mg/l nitrate in 50 and 150 cm depth. During 1996 and 1997 the stand uphill of the monitoring plot died off. As a consequence nitrate concentrations increased anew in 150 cm depth up to about 50 mg/l mainly due to nitrate enriched water transported by interflow. In contrast, concentrations in the upper soil layers, mainly influenced by vertical percolation, showed only weak reactions. In both cases of increased

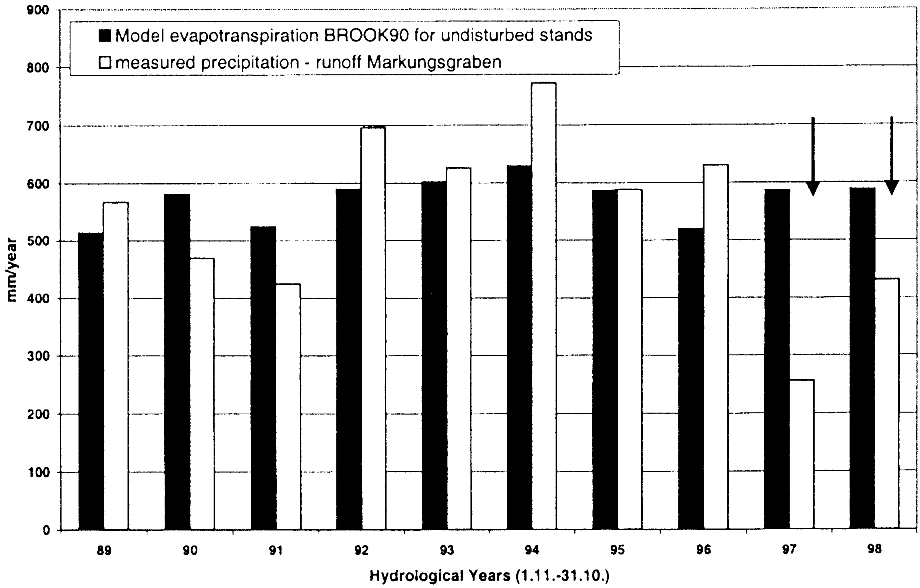


**Fig. 4.** – Comparison of modelled annual evapotranspiration with measured annual precipitation minus runoff for subcatchment "Markungsgraben".

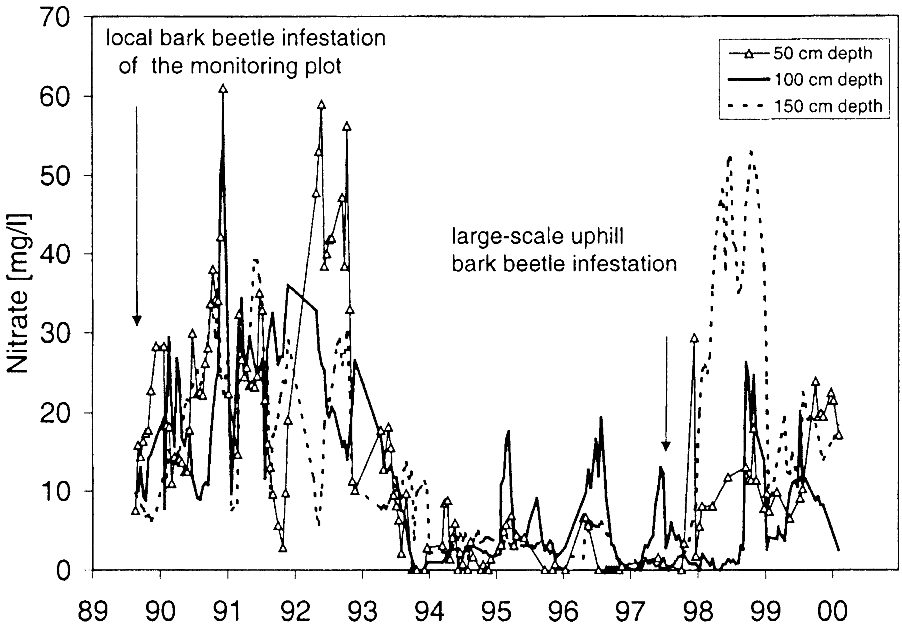


**Fig. 5.** – Nitrate concentrations in seepage water from three depths on the experimental plot spruce F1 in the subcatchment "Markungsgraben", altitude 970 m a.s.l.. Arrows indicate times of local and large-scale uphill bark beetle infestation of trees.

nitrification a dilution of the nitrate pulse took place with nitrate-poor water, in the first case (1990) with interflow water and in the second case with seepage water. This interplay of interflow and high small-scale spatial variability in forest development is typical for the slope region in the "Grosse Ohe" catchment. In the highlands the same processes occur, but their dynamics and intensities are prolonged compared to those of the slope region due to different site conditions (lower temperature, higher precipitation, longer lasting snow-cover, shorter vegetation period) (HUBER 2000, pers. comm.). For comparison, in the "Forellenbach" study (820 m a.s.l.) maximum nitrate concentrations in seepage water below spruce reached 190 mg/l two years after the bark beetle infestation (BEUDERT 1999). At this site lateral soil water flow is not likely due to rather flat terrain. In addition it has to be taken into account that seepage water quality is altered during further passage through the unsaturated zone and in the aquifer itself.

Seepage allows to monitor small-scale forest ecosystem changes, which are not easily upscaled, whereas the monitoring of spring, ground and stream water enables studies on a larger scale (Fig. 6). The worst case of a nearly complete die-off of spruce stands can be observed in the "Markungsgraben" catchment. Here nitrate concentrations in the stream water increased markedly. In fall 1998 and in 1999 nitrate concentrations reached 23 mg/l. Similar peak concentrations (fall 1998: 21,8 mg/l, spring 1999: 24,0 mg/l, fall 1999: 21,8 mg/l, spring 2000: 22,9 mg/l) were found in a high-elevation spring (1010 m a.s.l.) with a high proportion of interflow from soil layers with granitic blocks and complete die-off of spruce stands in its catchment area. Despite this large-scale die-off the nitrate concentrations increased only moderately compared to seepage water (Fig. 5). This is probably due to the fast development of formerly suppressed beech in the spring catchment, which starts to develop more freely after the spruce die-off and thereby consumes corresponding nitrate amounts. Until 1996 aluminium concentrations in spring water were below 1 mg/l. With the increase

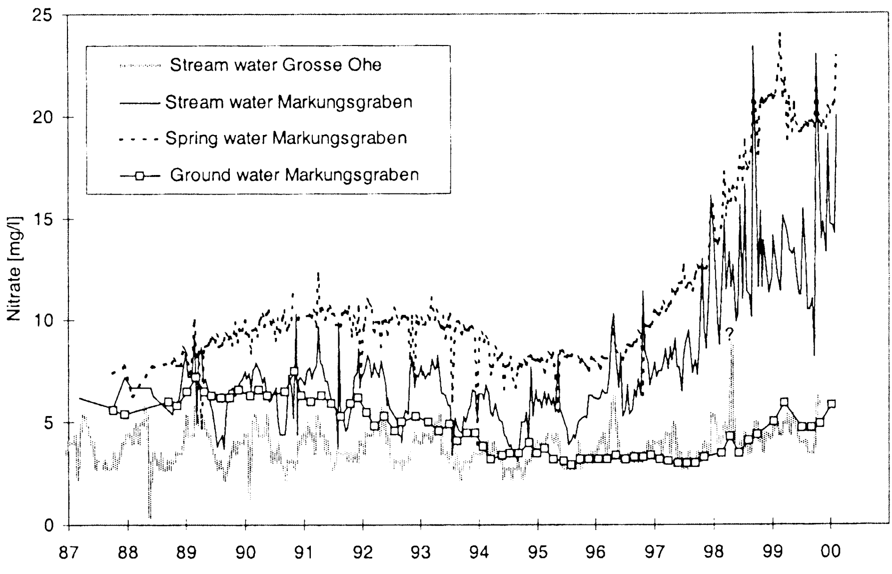


Fig. 6. – Nitrate concentrations in stream, spring and ground water in the subcatchment "Markungsgraben" and in the stream water of the "Grosse Ohe".

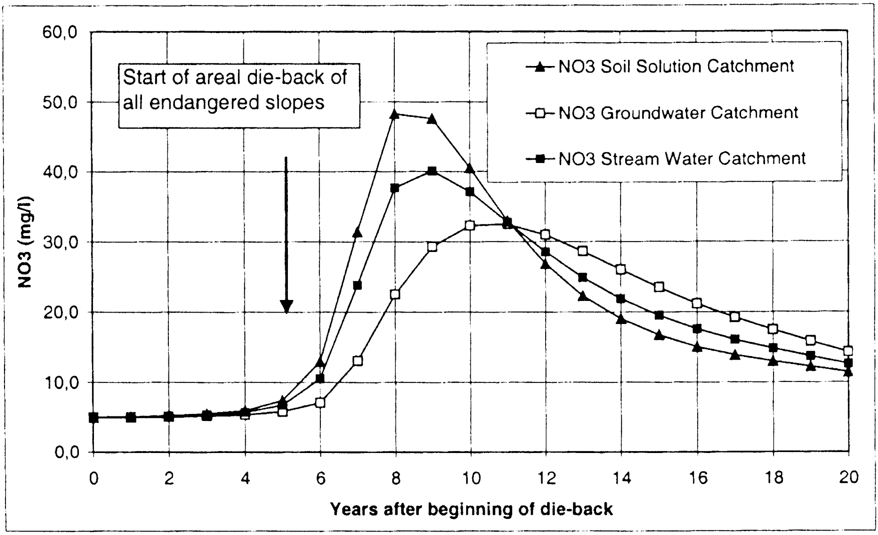


**Fig. 7.** – Modelled time series of $NO_3^-$ concentrations in the "Grosse Ohe" catchment for the die-off scenario (all endangered slope areas die within two years, no nitrogen uptake by secondary vegetation).

of nitrate aluminium increased too, but with peak concentrations below 2 mg/l. This strong release of aluminium due to excess nitrification can be seen also in seepage and stream water (see MORITZ & BITTERSOHL 2000). In the "Markungsgraben" catchment the ground water level is in 5–10 m depth. Starting in 1999, nitrate in the ground water exhibits a seasonal pattern with a peak in spring (6 mg/l). The increase of nitrate concentrations in the ground water lags two years behind that of stream and spring water. In the "Forellenbach" catchment nitrate concentrations in the ground water are still below 10 mg/l but increased during the last 1 1/2 years (BEUDERT 2000, pers. comm.). In the "Markungsgraben" catchment interflow above the dense basic series of the pleistocene periglacial cover sediment obviously transports excess element loads directly into the surface waters. Until October 1999 nitrate concentrations in the stream water of the "Grosse Ohe" show no definite increase with peaks values below 6 mg/l. Despite temporarily high nitrate concentrations in the soil solution, ground and stream water nitrate concentrations of about 4–12 mg/l on average can be classified as moderate. Springs with a high proportion of interflow and dead trees in their catchment area like the "Markungsgraben" spring represent a worst case situation. However, the maximum contaminant level for drinking water in Germany is 50 mg/l, so even these springs are well below.

## Model Application

Taking into account that around 73 % of the original forested slope area are endangered the question arises about the future development of water quality. A nitrogen budget model allows for a first assessment of future nitrogen release and its influence on the development of water quality (ZIMMERMANN & al. 1999). The model operates on an annual time-step and takes all nitrogen-relevant compartments (e.g. litter, humus, stem biomass) of the ecosystem into account. The nitrogen pools in each compartment are coupled by fluxes controlled by decomposition, mineralisation or immobilisation. Fluxes like deposition and vegetation uptake are also included. For the whole catchment the output signal is found by superimposing the response of undisturbed areas with the one from areas with dead trees. As a worst case scenario after 5 years of minor damages a complete die-off of all endangered slope areas within two years was assumed without considering uptake from the understorey (Fig. 7). Soil water showed the highest concentrations (nearly 50 mg/l) in an immediate reaction one year after the end of the die-off. Stream water concentrations reached almost 40 mg nitrate/l one year later, while the peak in the groundwater reached a maximum of around 30 mg/l two further years later. This delay fits to the observations. The model is sensitive to the assumptions of ground water proportion of discharge (30%), size of the ground water reservoir (1000 mm) and increase of percolation (+100 mm). A sensitivity analysis showed that if these parameters are changed within plausible limits known from previous studies the nitrate levels in each water kept below 60 mg/l, but their relations to each other were significantly changed. From this it can be concluded that the model results relating to the predicted level can be taken as quite certain. Nevertheless further studies will be conducted in this field. In the model the response is rather prolonged due to the assumption of lacking uptake by secondary vegetation, so that the original status is not reached before 20 years after the disturbance. An earlier simulation with the more detailed element budget model NuCM for the catchment Grosse Ohe resulted in peak concentrations of around 30 mg/l nitrate in stream and ground water four to six years after complete die-off (Kennel 1998). The peak in ground water lagged two years behind the stream water. This prediction also keeps below the above-mentioned simulation results.

## Conclusions

The massive die-off of spruce leads to a reduction in evapotranspiration, confirmed by the increase in runoff and by the water budget modelling. As previously found in other experiments, a threshold for a reaction of the discharge is exceeded if around 25 % of the catchment area are affected.

Peak concentrations in seepage water one to two years after the disturbance reach values of 60–190 mg/l, but are diluted by contributions from undisturbed areas depending on hydrological flow-paths and transformed by the further passage through the deeper underground or riparian zones along the streams. This effect can be seen when looking at maximum concentrations in surface and spring waters. Here even in the third year after a large-scale die-off nitrate keeps below 25 mg/l. From studies in Scandinavia (Wiklander & al. 1991), Germany (Hüser & al. 1996, Kölling & Moritz 1995, Mellert & al. 1996) and Great Britain (Reynolds & al. 1995) it is known that peak nitrate levels in stream water were found one to two years after the disturbance. Elevated nitrate levels were lasting four to five years until enough secondary vegetation developed.

Much lower concentrations can be found in the ground water (<10 mg/l), since the largest portion of nitrate loaded water is transported directly by interflow to surface waters. It seems that a lag period of one to two years of peak values in seepage water to ground water can be found in this area. Modelling by an annually based nitrogen turnover model showed in a worst-case scenario nitrate concentrations exceeding the measured values by 60%, but matches the observed time lag and specific concentration level for each water type. From the present knowledge nitrate in surface, spring and ground waters will keep below the maximum contaminant level of drinking water, so no danger for drinking water supply can be deduced. The effects from died-off areas will ease off in the next years due to regeneration of forest and ground vegetation, so the future development strongly depends on the further weather-induced spreading of the bark beetles in the lower regions of the National Park.

**Acknowledgement.** Funding for L. Zimmermann was provided through a research project (V50) financed by the Bavarian State Ministry of Food, Agriculture and Forestry.

## Literature

BAUMGARTNER A., 1958: Nebel und Nebelniederschlag als Standortsfaktor am Großen Falkenstein (Bayerischer Wald) [Fog and occult precipitation as site factor at the Grosse Falkenstein (Bavarian Forest)]. *Forstw. Cbl. 77: 257–272 (in German).*

BEUDERT B., 1999: Veränderungen im Stoffhaushalt eines abgestorbenen Fichtenökosystems im Forellenbachgebiet des Nationalparks Bayerischer Wald [Changes in the element budget of a died-off spruce ecosystem in the „Forellenbach" area of the Bavarian Forest National Park]. *Wasserhaushalt und Stoffbilanzen im naturnahen Einzugsgebiet Grosse Ohe 7: 93–106 (in German).*

BEUDERT B. & W. KANTOR W., 1999: Water and element budgets in the Forellenbach area of the Bavarian Forest National Park. *Silva Gabreta 3: 49–64.*

BRAUN G., PREUHSLER T. & GIETL G., 1999: Der Forschungsschwerpunkt Grosse Ohe [Research focus Grosse Ohe]. *Wasserhaushalt und Stoffbilanzen im naturnahen Einzugsgebiet Grosse Ohe 7: 7–12 (in German).*

ELLING W., BAUER E., KLEMM G. & KOCH H., 1987: Nationalpark Bayerischer Wald. Klima und Böden [Bavarian Forest National Park. Climate and soils]. *Schriftenreihe Nationalpark Bayerischer Wald 1, 2. Aufl. Verlag Morsak Grafenau, 255 pp., (in German).*

FEDERER C.A., 1997: BROOK90 : A Simulation Model for Evaporation, Soil Water and Streamflow Version 3.2 Computer share ware and documentation. *USDA Forest Service, Durham, NH, USA.*

HAAG I., 1997: Hydrochemische Dynamik und Versauerungsmechanismen im Quellgebiet der Grossen Ohe [Hydrochemical dynamics and mechanisms of acidification in the spring area of the Grosse Ohe]. *Wasserhaushalt und Stoffbilanzen im naturnahen Einzugsgebiet Grosse Ohe 6: 144 pp.*

HÜSER R., FÜHRER H.-W. & REHFUESS K.E., 1996: Wasserchemische Auswirkungen von Hiebseingriffen im Krofdorfer Buchenforst [Hydrochemical effects of forest-cuts in the beech stand of Krofdorf]. *Forst und Holz, 51 (20): 666–672 (in German).*

IBK (INSTITUT FÜR BIOKLIMATOLOGIE), 1998: Bericht zum Integrated Monitoring - Programm an der Meßstelle Forellenbach im Bayerischen Wald [Report from the Integrated Monitoring programme at the observation site Forellenbach in the Bavarian Forest]. *Göttingen (in German).*

IBK (INSTITUT FÜR BIOKLIMATOLOGIE), 2000: Sicherstellung des Integrated Monitoring -Programmes an der Meßstelle Forellenbach im Bayerischen Wald. [Securing the Integrated Monitoring Programme at the observation site Forellenbach in the Bavarian Forest]. *Final report (FKZ 351 01 006/03), Göttingen (in German).*

KENNEL M., 1998: Modellierung des Wasser- und Stoffhaushaltes von Waldökosystemen- Fallstudien: Forsthydrologisches Forschungsgebiet Krofdorf, Referenzeinzugsgebiet Grosse Ohe [Modelling of water and element budgets of forest ecosystems – Case studies: Forest hydrological experimental area Krofdorf, benchmark catchment Grosse Ohe]. *Forstliche Forschungsberichte Munich 168, 392 pp. (in German).*

KÖLLING C. & MORITZ K., 1995: Episodische Versauerung eines Fließgewässers (Metzenbach/Spessart) nach schweren Waldschäden durch Sturmwurf [Episodic acidification of a surface water (Metzenbach/Spessart) after severe forest damages through wind-throw]. *Informationsberichte des Bayerischen Landesamtes für Wasserwirtschaft 3/95: 91–96 (in German).*

MELLERT K.-H., KÖLLING C. & REHFUESS K.E., 1996: Stoffauswaschung aus Fichtenwaldökosystemen Bayerns nach Sturmwurf [Element leaching from spruce ecosystems in Bavaria after wind-throw]. *Forstw. Cbl. 115: 363–377 (in German).*

MORITZ K. & BITTERSOHL J., 2000: Turnover of nitrogen and acidification in the small headwater catchment Markungsgraben. *Silva Gabreta 4: 63–70.*

MORITZ K., BITTERSOHL J., MÜLLER F.X. & KREBS M., 1994: Auswirkungen des Sauren Regens und des Waldsterbens auf das Grundwasser. Dokumentation der Methoden und Meßdaten des Entwicklungsvorhabens 1988–1992 [Effects of acid rain and forest decline on ground water. Documentation of methods and data of the development project 1988–1992]. *Bavarian State Office of Water Management, Munich, Materials No. 40, 387 pp. (in German).*

NUESSLEIN S. & FAISST G., 1998: Waldentwicklung im Nationalpark Bayerischer Wald 1998. Totholzflächen und Waldverjüngung [Forest development in the Bavarian Forest National Park. Areas with dead trees and forest regeneration]. *Bayerisches Landesanstalt für Wald und Forstwirtschaft-Dokumentation, 24 pp. (in German).*

NUESSLEIN S., FAISST G., MORITZ K., ZIMMERMANN L., BITTERSOHL J., KENNEL M., TROYCKE A., ADLER H., 2000: Zur Waldentwicklung im Nationalpark Bayerischer Wald 1999 [Forest development in the Bavarian Forest National Park 1999]. *LWF-Berichte 25, 47 pp. (in German).*

PAHL S., 1996: Feuchte Deposition auf Nadelwäldern in den Hochlagen der Mittelgebirge [Fog deposition of spruce forests at high-altitudinal sites of hills]. *DWD-Ber. 198 (in German).*

REYNOLDS B., ROBERTSON W.H., HORNUNG M. & STEVENS P.A., 1995: Forest manipulation and solute production; modelling the nitrogen response to clearcutting. *In: Solute modelling in catchment systems*, TRUDGILL, S.T. (ed.). *John Wiley, Chichester, UK, 211–233.*

STEDNICK J.D., 1996: Monitoring the effects of timber harvest on annual water yield. *Journal of Hydrology 176 (1–4): 79–95.*

THUMS S., 1991: Niederschlags- und Abflussauswertung der 10jährigen Meßreihe 1980–89 für das Einzugsgebiet Grosse Ohe [Precipitation and discharge analysis of the 10 year term record 1980–89 for the catchment "Grosse Ohe"]. *Wasserhaushalt und Stoffbilanzen im naturnahen Einzugsgebiet Grosse Ohe 5, 197 pp. (in German).*

VITOUSEK P.M. & MELLIO J.M., 1979: Nitrate losses from disturbed forests: Patterns and mechanisms. *Forest Sci. 25: 605–619.*

WIKLANDER G., NORDLANDER G. & ANDERSSON R., 1991: Leaching of nitrogen from a forest catchment at Söderrasen in Southern Sweden. *Water, Air and Soil Pollution 55: 262–282.*

ZIMMERMANN L., MORITZ K., KENNEL M. & BITTERSOHL J., 1999: Auswirkungen von flächigem Borkenkäferbefall auf Wassermenge und Gewässerqualität [Impacts of bark beetle mass propagation on quantity and quality of waters]. *Wasserhaushalt und Stoffbilanzen im naturnahen Einzugsgebiet Grosse Ohe 7: 125–136 (in German).*