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The hydrogeology of a catchment area and an artificially divided dystrophic lake – consequences for the limnology of Lake Fuchskuhle

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Abstract. The hydrogeology between the catchment area and the divided dystrophic Lake Fuchskuhle with respect to the genesis and the land–water interactions were investigated. Water levels at numerous locations in the catchment area were measured in order to characterize the hydrology. The water balance of the area was calculated based on long term climatic investigations. The geology of the peat was documented at 25 sampling points by cores collected with a peat drill. Chemical parameters including pH, total phosphorus and total nitrogen concentrations, DOC concentration, colour (SAK 436 m^{-1}) and the UV_{254}/DOC ratio in the catchment area and in two compartments (NE and SW compartment) were determined. The chemical fluxes of DOC, nitrogen and phosphorus from the catchment area into one compartment (SW compartment) were determined. During the genesis of the Lake Fuchskuhle area two aquifer systems (local peat aquifer, regional sandy main aquifer) developed. Both aquifers are largely independently with almost no lateral interactions. Two compartments are supplied with water from the local peat aquifer. From the other two compartments, however, water is flowing out into the peat body. During high groundwater inflow into the SW compartment higher concentration of DOC, nitrogen and phosphorus in the SW compartment were detected. The fen can be divided in two parts: in the meso – to eutrophic fen northwest and the mainly meso – to oligotrophic – acid fen in the southeast. The significant differences in parameters such as pH, conductivity and DOC concentration gave a clear picture of the heterogeneity of the two compartments and their dependence on the catchment area with the two aquifers.

Introduction

Lakes are integrated into the global water cycle and are, therefore, influenced by precipitation, evaporation and water fluxes by groundwater or surface water. In addition to biotic and abiotic activities within the lakes; organic

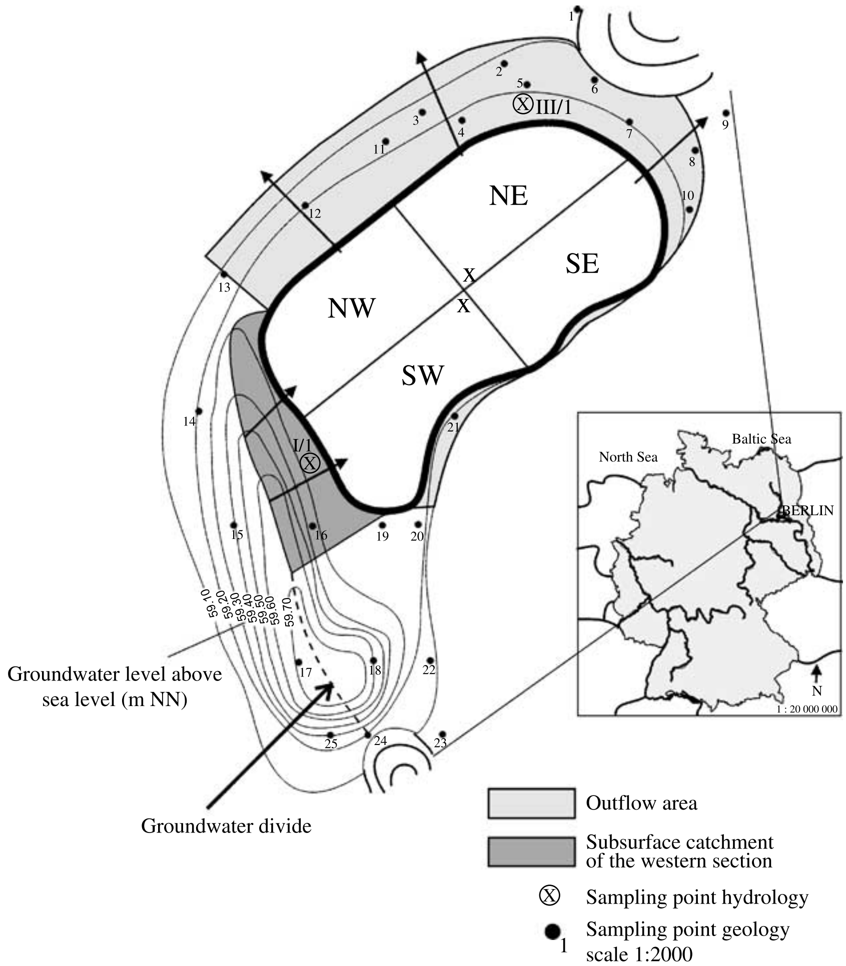

Fig. 1. Lake Fuchskuhle: location of the lake in the Mecklenburg–Brandenburg Lake District in north east Germany and the hydrogeology of the catchment area and the compartments (main map). The figure originates partly from Sachse et al. (2001).

material, nutrients, and elements from the surroundings will be transferred via the water flow into the system. Terrestrial ecosystems are proposed as the dominant organic carbon source for surface waters (Wetzel 1975; Thurman 1985; Hemond 1990; Mulholland et al. 1990). Mulholland and Hill (1997) found in their investigations a strong impact of the catchment area on seasonal patterns of nutrients and DOC concentrations in stream water.

Other investigations have shown that organic carbon concentrations in runoff waters from wetlands are much higher than in runoff waters from well drained mineral soils (Mulholland & Kuenzler 1979; Hemond 1990; David

& Vance 1991). The leaching of organic carbon, however, may depend on soil structure and porosity, particularly peat, on sorption processes occurring along the water gradient, and on biological degradation (Dickinson 1983; Wetzel 1992; Succow & Joosten 2001).

Wetlands are effective in delaying storm run-off by retention the surface water, by preventing soil erosion and by retention and storage of nutrients and DOC (Soulsby et al. 1998, 2002). Investigations in the Scottish uplands on hydrological control of water chemistry showed the essential role of peat in regulating the quantity and quality of surface waters (Soulsby et al. 2002).

This study focuses on the hydrogeology of a small lake and the catchment area with respect to the genesis. The water balance between lake and catchment area and chemical fluxes were of main interest. Lake Fuchskuhle was chosen for this investigation because it was artificially subdivided into four compartments (Kasprzak et al. 1988; Kasprzak 1993) (Fig. 1). The four compartments have subsequently developed divergent chemical and biological characteristics (Kasprzak 1993; Koschel 1995; Bittl 1999; Hehmann et al. 2001; Sachse et al. 2001; Chan et al. 2002). Investigations on the composition of the DOC pool indicated remarkably differences between the compartments of Lake Fuchskuhle (Bittl 1999). Sachse et al. (2001) stated the impact of the catchment area on these differences in DOC composition. Based on the results of Bittl (1999) and Sachse et al. (2001) further detailed investigations on the hydrogeological system (including the genesis) within the peat body were needed in order to quantify the monthly inflow of the groundwater and the transport of DOC and nutrients from the catchment area into the compartments of Lake Fuchskuhle. The following questions are addressed in this paper: (i) the detailed hydrogeological system that developed in the Fuchskuhle area (ii) the water balance between the catchment area and the lake (iii) chemical fluxes of DOC and nutrients.

Material and methods

Study site

The dystrophic Lake Fuchskuhle is situated in the Mecklenburg–Brandenburg Lake District in northeast Germany (Fig. 1). The area forms part of the large outwash plain in the southwest foreland of the Fürstenberger end moraine from the Weichsel glacial period. End moraine, ground moraine, outwash plain and glacial spillways such as Lake Fuchskuhle typify this landscape. The surface area of the lake is 14,930 m^2, the median depth is 3.3 m and its catchment is 5000 m^2 (Table 1). This constitutes a rather small area, which is easily comprehensible. The climate of the area is characterized by a transition

Table 1. Volume, surface, depth and water balance of the catchment area and the compartments of Lake Fuchskuhle.

	Lake Fuchskuhle	SW compartment	NW compartment	NE compartment	SE compartment
Volume (m^3)[a]	41570	9700	10630	11300	9940
Surface (m^2)[a]	14930	4430	3680	3360	3460
Maximum depth (m)[a]	5.5	4.5	5.0	5.5	4.9
Catchment area (peat aquifer) (m^2)	5000	3000	2000	0	0
Groundwater recharge (peat aquifer) (m^3/year)[b]	694	416	278	0	0
Groundwater flow from peat aquifer to lake (m^3/year)[c]	715	429	286	0	0
Groundwater flow from lake to peat aquifer (m^3/year)[c]	1090	250	228	260	352
Surface water recharge (m^3/year)[b]	1229	–	–	–	–
Leakage effects (partial supply of the main aquifer, m^3/year)	854[d]	–	–	–	–

[a]From Kasprzak (1993).
[b]Calculation based on mean precipitation over 40 years (1962–2001).
[c]Calculation by Darcy's Law, measurements 2000/2001.
[d]Including catchment area.

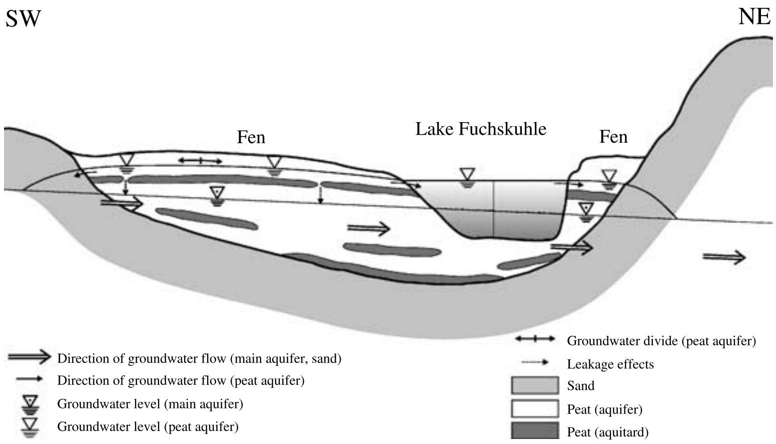

Fig. 2. Cross-section of Lake Fuchskuhle and the adjacent fen showing directions of groundwater flows and levels (scheme).

from maritime to continental influence with a dominant maritime character and a median precipitation of 659 mm per year (Richter 1997). Lake Fuchskuhle is connected to a fen of *Ledo-Pinetum* vegetation (Succow & Jeschke 1986) on two sides, which is extensive in the southwest and rather small in the northeast (Fig. 2). Forest of *Myrtillo-Pinetum* vegetation surrounds the lake and fen. The lake has no inlet or outlet, but is fed by rain and groundwater. In 1986 the naturally acidic lake was subdivided into two and in 1989 into four compartments by plastic curtains: southwest (SW), northwest (NW), northeast (NE) and southeast (SE) (Kasprzak et al. 1988; Kasprzak 1993) (Fig. 1). The volume of the compartments lay between 9700 m^3 in the SW and 11,300 m^3 in the NE (Table 1). The surface of the compartments range between 3360 m^2 in the NE and 4430 m^2 in the SW (Table 1). Investigations on the water balance of the area have been carried out since 1957 (Richter 1997), based on a dense network of measuring points for precipitation, levels of groundwater, and lake levels. The hydrogeological investigations in the Stechlin area, which includes the catchment area of Lake Fuchskuhle, began in 1995 (Ginzel & Handke 1995; Ginzel 1999, 2000). A groundwater divide developed in the peat adjacent to the SW compartment of Lake Fuchskuhle, which makes it possible to differentiate an individual subsurface catchment area for both western compartments of the lake (Sachse et al. 2001). From this part of the peat body, the groundwater of the fen is flowing into the SW and NW compartments (Sachse et al. 2001). In contrast, the NE and SE compartments have no influx from the peat, water from both compartments is flowing out into the peat body (Sachse et al. 2001).

Due to the division and a moderately wind-induced mixing of the water in the compartments, the lake has been stratified from spring to autumn, with a metalimnion between 2 and 3 m deep and with an anoxic zone near the sediment which can reach the metalimnion during summer. Since the division, the compartments developed divergent physical and chemical parameters (Kasprzak 1993; Koschel 1995; Bittl 1999; Sachse et al. 2001), microbial activity (Bittl & Babenzien 1996; Bittl 1999; Chan et al. 2002), abundance and structure of phytoplankton communities (Hehmann & Krienitz 1996; Hehmann et al. 2001), and structure of the food web (Simek et al. 1998).

Hydrogeological investigations

Measurements of the water level were made between 18 April 2000 and 31 December 2001 at 2 week intervals at:

- 14 wells in the peat aquifer (groundwater level),
- 17 wells in the main aquifer (groundwater level),
- 1 measuring point in the NE compartment of Lake Fuchskuhle (surface water).

The groundwater flow from the peat aquifer to the lake (SW and NW compartment) and the groundwater flow from the lake (SE and NE compartment) out to the peat aquifer, is calculated per year and also monthly by Darcy's Law: rate of groundwater flow $(Q) = B \times M \times G \times k_f$, where B is the width of flow (m), M the thickness of the aquifer (m), G the falling gradient of groundwater (parts per mille) and k_f the permeability coefficient (m/s). The calculation per year is based on the mean precipitation determined over 40 years (1962–2001) (Richter 1997). The calculation per month is based on the precipitation determined by the Deutscher Wetterdienst (German weather service) in Neuglobsow. The chemical fluxes of DOC, phosphorus and nitrogen from the catchment area into the SW compartment are calculated multiplying the nutrient and DOC concentrations (measured in the well I/1 peat) by the determined groundwater flow.

The wells were made of polyvinylchloride-KT and had openings of 0.3 mm in diameter through which to collect the interstitial water of the fen.

From 10 April 2001 to 12 April 2001 the geology of the peat body was documented at 25 sampling points (Fig. 1) by cores collected with a peat drill. The cores were 50 cm long and had a diameter of 5 cm. The botanical structure and the rate of decomposition of the peat body were analysed per common field methods by squeezing of the sample and using magnifying glass for analyses.

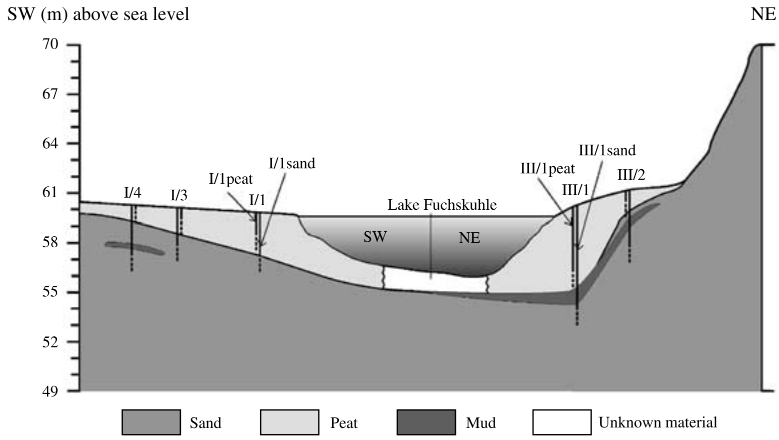

Fig. 3. Morphology of Lake Fuchskuhle and the catchment areas with sampling points: well I/1-peat, well I/1-sand, well III/1-peat and well III/1-sand (scheme).

Sampling and measurements of physical and chemical parameters

The investigation was carried out monthly from September 2000 until September 2001 in two compartments (SW and NE) of the lake and in two wells (I/1 and III/1) of the catchment area. The SW and NE compartments were chosen for the study because differences in water chemistry were most pronounced. The water samples of both compartments were taken in the morning at a depth of 0.5 m with a Limnos-sampler.

The two wells chosen were: I/1-peat, which is located in the fen adjacent to the SW compartment, and III/1-peat, which is located in the fen adjacent to the NE compartment (Fig. 3). The groundwater chemistry of the wells are representative of the entire catchment area. Both wells are closest located to the adjacent compartments and were therefore chosen. For comparison of the physical–chemical parameters between the peat aquifer and the main (sand) aquifer in the catchment areas of the SW and NE compartments, well I/1-peat and I/1-sand, and at the other side of the lake, well III/1-peat and III/1-sand, were investigated (Fig. 3). The wells were emptied with a boat pump, samples were collected after the wells refilled with interstitial water. The sampling flasks were filled, avoiding air bubbles, to minimize oxygen contact. All samples were immediately taken to the laboratory.

In the SW and NE compartment, and in the I/1-peat and III/1-peat wells, the following physical and chemical parameters were recorded: pH, temperature, conductivity, concentration of dissolved organic carbon (DOC), water colour (SAK 436) and content of unsaturated aromatic structures on DOC (SAK 254/ DOC), concentrations of total phosphorus and total nitrogen. The samples were frozen at $-20\,^{\circ}$C until total phosphorus and total nitrogen concentrations were determined. The spectrophotometric measurements (SAK 436, SAK 254) were done within 2 h after sampling. The samples for analyses of DOC were kept frozen at −30 °C (measured as non-purgeable organic carbon, NPOC). Measurements were made with a Shimadzu total organic carbon analyser TOC-5050 (Zwirnmann & Dietrich 1999a) within 2 months. The water colour was defined according to the European standard (EN ISO 7887:1994). The determination of the portion of unsaturated, aromatic structures of the DOC was made with a Beckman spectrophotometer DU 650 measuring the absorbance at $\lambda = 436$ nm and at $\lambda = 254$ nm respectively, using 1 cm quartz cells and purified water as the reference. The relationship between SAK (λ)/DOC served as the specific absorption coefficient, and is expressed in $l\,mg^{-1}\,m^{-1}$ (Sontheimer et al. 1995). The specific spectral absorbance at $\lambda = 254$ nm (SAK (254 nm/DOC)) reflects the valence electrons and unsaturated, aromatic character of the structure of humic substances (Korshin et al. 1998, 1999a). Prior to measurements of absorbance, the samples were filtered with a membrane filter of 0.45 μm pore size. With each determination, the pH and temperature of the filtered sample were recorded. The measurements of total phosphorus and total nitrogen were made with the Perstop flow injection analysis system TECA FIA STAR 5010/5030 (Tecator Application Notes (ASN) 60-03/83 for TP – detection limit 0.005 $mg\,l^{-1}$; ASN 110-03/92 for TN – detection limit 0.01 $mg\,l^{-1}$). In September 2000 and August 2001 mixed samples taken at 0 and 2 m depth were analysed for total phosphorus. Temperature, pH and conductivity were measured in the field by using probes (OXI 196 resp. pH 196 T, WTW Weilheim).

In June 2002 the peat aquifer with the main aquifer were compared by determining: pH, conductivity, magnesium, calcium, DOC, total phosphorus and total nitrogen. Total phosphorus and total nitrogen were determined by the flow injection analysis system Foss-5012 Analyser (Zwirnmann et al. 1999b). Samples for calcium and magnesium analysis were stored at room temperature at pH 2 and analysed within 48 h by atomic absorption spectroscopy (AAS 3300 of Perkin Elmer) (Zwirnmann et al. 1999b).

Results

Hydrogeology

The results of the hydrogeological investigations are presented in Fig. 2 and Table 2. The outwash plain is an uncovered aquifer, up to 50 m thick, and is composed of complex sediment and other underlying glacial fluviatile deposits; this is the main aquifer of the area. Lake Fuchskuhle and the adjacent fen occupy a hollow above the field of groundwater flow of the main aquifer

Table 2. Geological investigation of the peat body at 25 sampling points at different depths.

Sampling point	Depth (m)	Type of peat
1	0.20	Peat[a]
2	0.50	Peat[a]
	1.05	Forest-swamp peat
	1.40	Peat mud
	1.70	*Sphagnum–Scheuchzeria* peat
	2.00	*Sphagnum* peat
3	0.50	*Sphagnum* peat
4	0.10	Peat[a]
	0.75	*Carex* peat
	1.90	Peat mud
	2.00	Forest-swamp peat
	2.25	*Carex* peat
	2.50	*Scheuchzeria* peat
5	0.25	*Sphagnum* peat
	0.50	*Carex* peat
6	0.50	Forest-swamp peat
7	0.40	*Sphagnum* peat
	0.50	*Carex-Sphagnum* peat
8	0.25	*Sphagnum* peat
	0.60	*Carex-Sphagnum* peat
	1.30	*Sphagnum* peat
	1.40	Peat mud
	2.00	*Sphagnum-Carex* peat
	2.55	*Sphagnum* peat
	2.80	Peat mud
	2.90	*Sphagnum* peat
	4.90	Peat mud
	5.00	*Scheuchzeria* peat
9	0.80	Forest-swamp peat
10	0.20	*Sphagnum* peat
	0.50	Forest-swamp peat
	1.70	Peat mud
	2.05	*Phragmitis-Carex* peat
	2.35	Medium sand
	2.55	*Phragmitis* peat
11	0.40	Forest-swamp peat
	0.50	*Carex* peat

Table 2. (continued)

Sampling point	Depth (m)	Type of peat
	1.40	Forest-swamp peat
12	0.60	Forest-swamp peat
	1.25	*Carex* peat
	1.30	Forest-swamp peat
	1.50	*Scheuchzeria* peat
	2.25	Peat mud
	2.50	*Sphagnum* peat
	2.65	Peat mud
	2.90	*Scheuchzeria* peat
13	0.50	Forest-swamp peat
	0.85	*Carex* peat
	1.00	*Scheuchzeria* peat
	1.80	*Carex* peat
	2.90	Peat mud
	3.85	*Scheuchzeria* peat
14	1.80	Peat[a]
	2.00	*Carex* peat
	2.50	*Scheuchzeria* peat
	2.95	Forest-swamp peat
15	1.00	Peat[a]
16	1.70	Peat[a]
	2.00	*Scheuchzeria* peat
	2.25	*Carex* peat
17	0.50	Peat[a]
18	1.60	*Sphagnum* peat
	2.00	*Carex-Scheuchzeria* peat
19	0.25	*Sphagnum* peat
	0.80	*Sphagnum* peat
	1.00	*Sphagnum* peat
	3.00	*Sphagnum* peat
		Weakly decomposed
	3.50	*Sphagnum–Scheuchzeria* peat
	4.00	*Scheuchzeria-Sphagnum* peat
	4.30	*Scheuchzeria* peat
20	1.00	Forest-swamp peat
21	0.50	*Sphagnum* peat
	1.10	Peat[a]
22	0.20	*Sphagnum* peat

Table 2. (continued)

Sampling point	Depth (m)	Type of peat
	1.30	*Sphagnum* peat
		Strongly decomposed
	1.40	*Scheuchzeria* peat
23	0.50	Peat[a]
	1.00	Forest-swamp peat
24	0.40	Peat[a]
25	0.50	Peat[a]
	1.00	Forest-swamp peat

[a]Undefined peat.

(Fig. 2). In the first stage of genesis, the hollow was an integrated part of the main aquifer and filled with water as a late glacial-early holocene lake. The surface and the groundwater were integrated into a hydraulic system. Initial sedimentation in the deeper parts of the lake was organogenic algal mud (limnic sequence) with an elastic consistency. The low permeability of the algal mud hydraulically sealed the water body from the main aquifer. In the NW part of the fen after sedimentation of the algal mud the lake was partially overgrown indicated by well conserved *Scheuchzeria* peat (telmatic sequence) (Table 2). Before overgrowth was completed, a significant increase of groundwater of the peat aquifer and the lake water level occurred, which is indicated by extended peat mud. Then, at a second stage of sedimentation (limnic sequence) predominantly eutrophic peat developed (*Carex* peat, *Phragmites* peat and forest-swamp peat) (Table 2). The result was a new stage of limnic sedimentation and of overgrowth, with new limnic and telmatic sequences in lithostratigraphy. Later during the development of the area a change from eutrophic to meso- or oligotrophic peat occurred, which is indicated by *Sphagnum* peat (Table 2). In the NE and SE part of the fen the telmatic sequence is characterized by a more meso- to oligotrophic vegetation (*Sphagnum* peat). In the NW part of the fen, highly degraded peat dominates; mud occurs here only in thin layers. However, in the NE and SE part of the fen, slightly degraded peat dominates. The fen can be divided in two parts: in the meso- to eutrophic fen northwest and the mainly meso- to oligotrophic – acid fen in the southeast (following the ecological system of mires developed by Succow (1988)).

With the first stage of sedimentation (algal mud), a second upper aquifer developed as a groundwater lens over the main aquifer. The second upper aquifer exists without lateral influx from the main aquifer (Fig. 2), normally

Table 3. Groundwater flow from the catchment area into the SW compartment and chemical fluxes of DOC, P and N into the SW compartment of Lake Fuchskuhle between September 2000 and August 2001.

Month	Groundwater flow (m^3 month^{-1})	DOC input (kg month^{-1})	(mg l^{-1})	P input (g month^{-1})	(µg l^{-1})	N input (kg month^{-1})	(mg l^{-1})
September 00	75.6	4.91	0.51	12.62	1.30	0.42	0.04
October 00	12.0	0.83	0.09	3.40	0.35	0.10	0.01
November 00	47.1	3.17	0.33	12.27	1.27	0.39	0.04
December 00	63.6	4.59	0.47	9.28	0.96	0.47	0.05
February 01	131.4	10.23	1.05	51.05	5.26	1.12	0.12
March 01	64.2	4.57	0.47	6.49	0.67	0.42	0.04
May 01	0[a]	0.00	0.00	0.00	0.00	0.00	0.00
June 01	14.4	1.02	0.11	1.82	0.19	0.09	0.01
July 01	0[a]	0.00	0.00	0.00	0.00	0.00	0.00
August 01	67.5	4.44	0.46	8.36	0.86	0.51	0.05

[a]Groundwater depletion.

water influx is exclusively by precipitation, but during intensive precipitation the influx of surface water from the slopes is added. In marginal parts of the hollow, the peat body ends and the water of the peat aquifer flows into the groundwater of the outwash plain and supplies the main aquifer.

Water balance and chemical fluxes

The water balance of the catchment area and Lake Fuchskuhle is summarized in Table 1. During the investigated period 715 m^3 $year^{-1}$ groundwater entered Lake Fuchskuhle via the peat aquifer. The SW compartment received 429 m^3 $year^{-1}$ and the NW compartment 286 m^3 $year^{-1}$. The groundwater flow from the SW compartment out to the peat aquifer was 250 m^3 $year^{-1}$ and from the NW compartment 228 m^3 $year^{-1}$. The NE and SE compartments received no groundwater from the peat aquifer but water from both compartments entered the peat aquifer, 260 m^3 $year^{-1}$ from the NE and 352 m^3 $year^{-1}$ from the SE.

The monthly groundwater flow from the peat aquifer into the SW compartment and the calculated chemical fluxes of DOC, phosphorus and nitrogen between September 2000 and August 2001 are listed in Table 3. The groundwater flow ranged from 12.0 m^3 in October 2000 to 131.4 m^3 in February 2001. In May and July 2001 groundwater depletion occurred.

The DOC input from the peat aquifer into the SW compartment ranged from 0.83 kg in October 2000 to 10.23 kg in February 2001. The input of phosphorus ranged from 1.82 g in June 2001 to 51.05 g in February 2001. The nitrogen input ranged from 0.09 kg in June 2001 to 1.12 kg in February

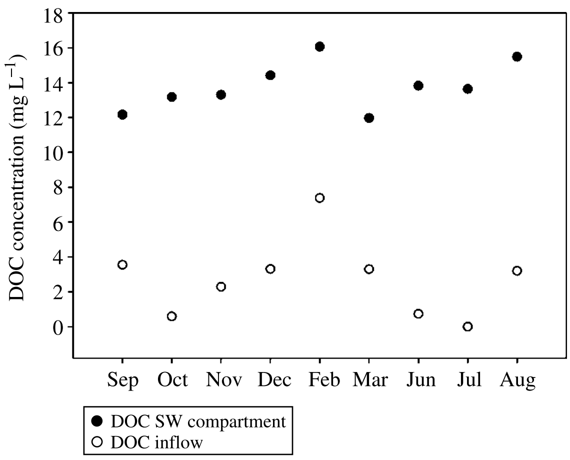

Fig. 4. DOC concentration in the SW compartment and additional supply (inflow) of DOC through the catchment area into the SW compartment. *Data multiplied by factor seven.

2001. The input of DOC, phosphorus and nitrogen were highest in February 2001. The connection between the DOC inflow into the SW compartment and the DOC concentration in the SW compartment is illustrated in Fig. 4. The DOC concentration in the SW compartment increased from September 2000 until February 2001. Simultaneously, the inflow of DOC from the catchment area increased from October 2000 until February 2001. From March 2001 until July 2001 the inflow of DOC decreased followed by an increase in August 2001. In comparison, the DOC concentration in the SW compartment decreased in March 2001 but increased afterwards until August 2001.

Physical and chemical parameters of the lake and the catchment area of the peat aquifer

The surface water of the SW and NE compartments of the lake and the catchment areas (well I/1 peat and well III/1 peat) differed significantly (*t*-test, $p < 0.05$) in three measured physical parameters: temperature, pH, and conductivity (Fig. 5(A–F)).

The temperature in the NE was usually higher than in the SW, because of differences in the intensity of solar radiation (Fig. 5(A)). The NE compartment is exposed to solar radiation nearly the whole day, whereas forest shades the SW compartment. The same effect can be seen for the catchment areas, with higher temperature in well III/1 which is adjacent to the NE compartment (Fig. 5(A and B)). The pH in the NE compartment ranged from 5.79 to 6.79 and in the SW compartment from 4.69 to 5.03 (Fig. 5(C)). In well III/1, adjacent to the NE compartment, the pH was between 5.65 and 6.08, and well I/1, adjacent to the SW compartment, the pH ranged from 4.16 to 4.56 (Fig. 5(D)). The conductivity throughout the year was higher in the SW compartment, 38–52 $\mu S\,cm^{-1}$, than in the NE compartment, 31–45 $\mu S\,cm^{-1}$ (Fig. 5(E)). The conductivity was higher in well III/1 (166–211 $\mu S\,cm^{-1}$) than in well I/1 (103–111 $\mu S\,cm^{-1}$) (Fig. 5(F)).

Total nitrogen and DOC differed significantly (*t*-test, $p < 0.05$, Figs. 6(C) and 7(A)) in the SW and NE compartments. The catchment areas (well I/1 peat and well III/1 peat) differed significantly in total phosphorus, total nitrogen and DOC (Figs. 6(B and D) and 7(B)) (*t*-test, $p < 0.05$). Furthermore, in the adjacent wells, the concentrations of total phosphorus, total nitrogen, and DOC were higher than in the compartments. The DOC concentrations in the SW compartment (12.2–16.1 $mg\,l^{-1}$, median $13.8 \pm 1.2\,mg\,l^{-1}$) were higher than in the NE compartment (8.2–13.2 $mg\,l^{-1}$, median $11.7 \pm 1.6\,mg\,l^{-1}$). Well I/1 (62.3–77.9 $mg\,l^{-1}$, median $69.5 \pm 4.9\,mg\,l^{-1}$) showed higher DOC concentrations than well III/1 (33.5–42.6 $mg\,l^{-1}$, median 36 ± 3.1) (Fig. 7(A and B)). The characterisation of the DOC per measurement of the water colour (SAK 436) and the portion of UV-absorbing, aromatic structures of the

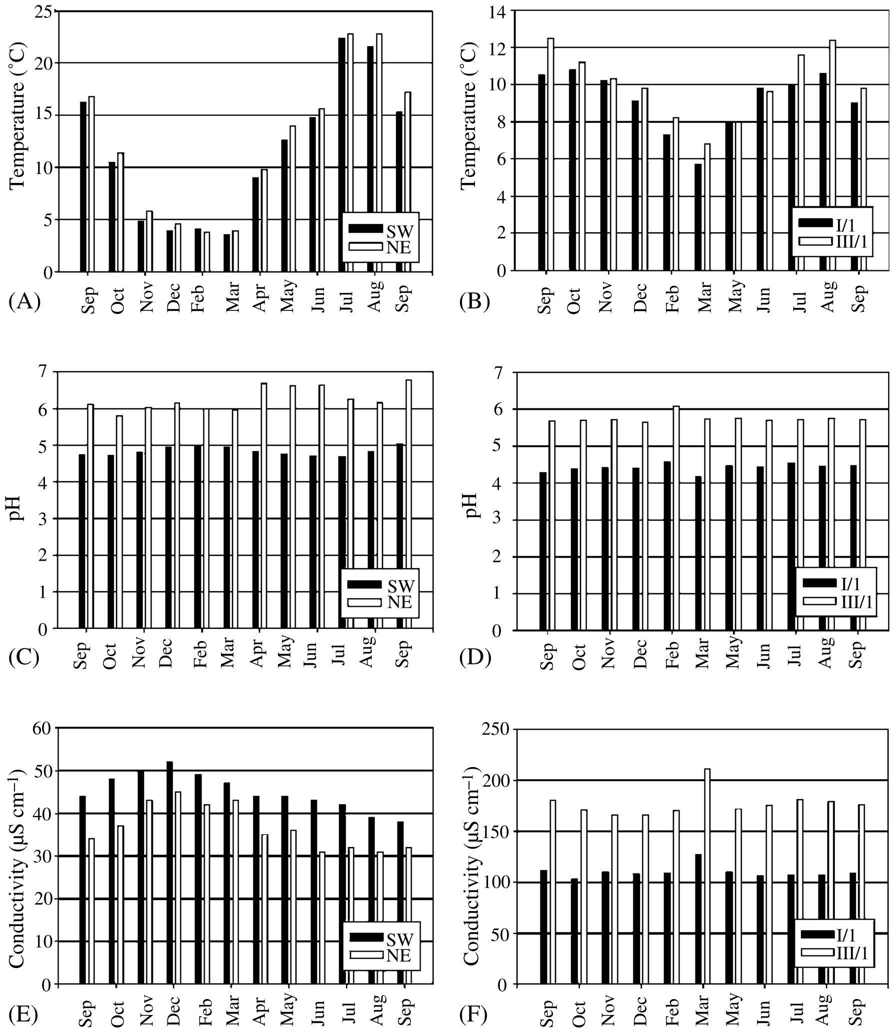

Fig. 5. Temperature – T (A + B), pH (C + D) and conductivity (E + F) of the SW and NE compartments and of the wells I/1-peat and III/1-peat from September 2000 until September 2001.

DOC (SAK (254)/DOC) gave an indifferent picture (Fig. 7(C–F)). The SW compartment showed higher values of the SAK 436 (0.5–1.5 m^{-1}) throughout the year than the NE compartment (SAK of 0.1–1.1 m^{-1}). The SAK 436 of well I/1 and well III/1 showed higher values (SAK of 2.0–5.14 m^{-1} and 4.0–11.9 m^{-1} respectively) than in both compartments. The highest values were determined in the adjacent well III/1 of the NE compartment. Hence, the SW compartment had more coloured water than the NE compartment. The waters

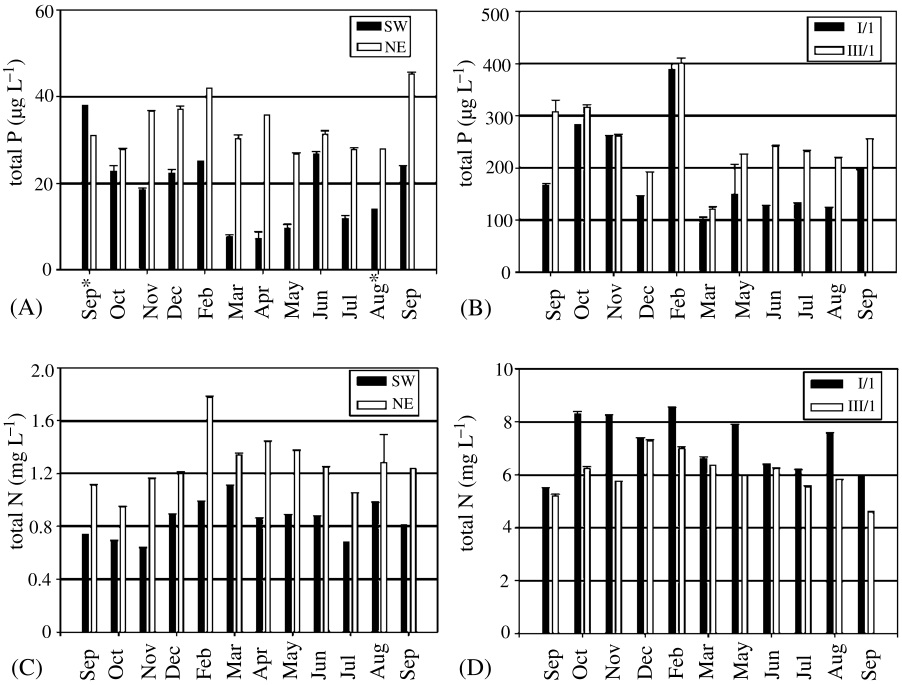

Fig. 6. Total phosphorus and total nitrogen concentrations of the SW and NE compartment (A + C) and of the wells I/1-peat and III/1-peat (B + D) from September 2000 until September 2001. *September 2000 and August 2001 mixture of samples from 0 and 2 m depth.

in the catchments were more coloured than the water in the compartments, but in contrast, the well in the SW catchment area had less coloured water than the well in the NE catchment area (Fig. 7(C and D)). The same pattern can be observed for the portion of UV-absorbing, unsaturated, aromatic structures of the DOC (Fig. 7(E and F)). The SW compartment showed higher ratios of the SAK 254/DOC quotient (2–2.8 $l\,mg^{-1}\,m^{-1}$, median 2.5 ± 0.3) than the NE compartment (1.1–2.7 $l\,mg^{-1}\,m^{-1}$, median 1.6 ± 0.5). The ratio of the SAK 254/DOC quotient in the adjacent well I/1 of the SW compartment, however, was 1.8–2.3 $l\,mg^{-1}\,m^{-1}$, median 1.9 ± 0.2, and in well III/1 2.2–3.8 $l\,mg^{-1}\,m^{-1}$, median 2.9 ± 0.5. Hence, the portion of UV-absorbing aromatic structure, such as humic substances, is higher in the SW compartment and in the catchments of the SW and NE than in the NE compartment.

The total phosphorus and total nitrogen concentrations in the NE compartment were higher than in the SW compartment except for two deviations in September 2000 and August 2001 for the nitrogen concentration (Fig. 6(A and C)). The total phosphorus concentration ranged from 25.6 to 45.3 $\mu g\,l^{-1}$ in the NE, and from 7.3 to 38.0 $\mu g\,l^{-1}$ in the SW. The total nitrogen concen-

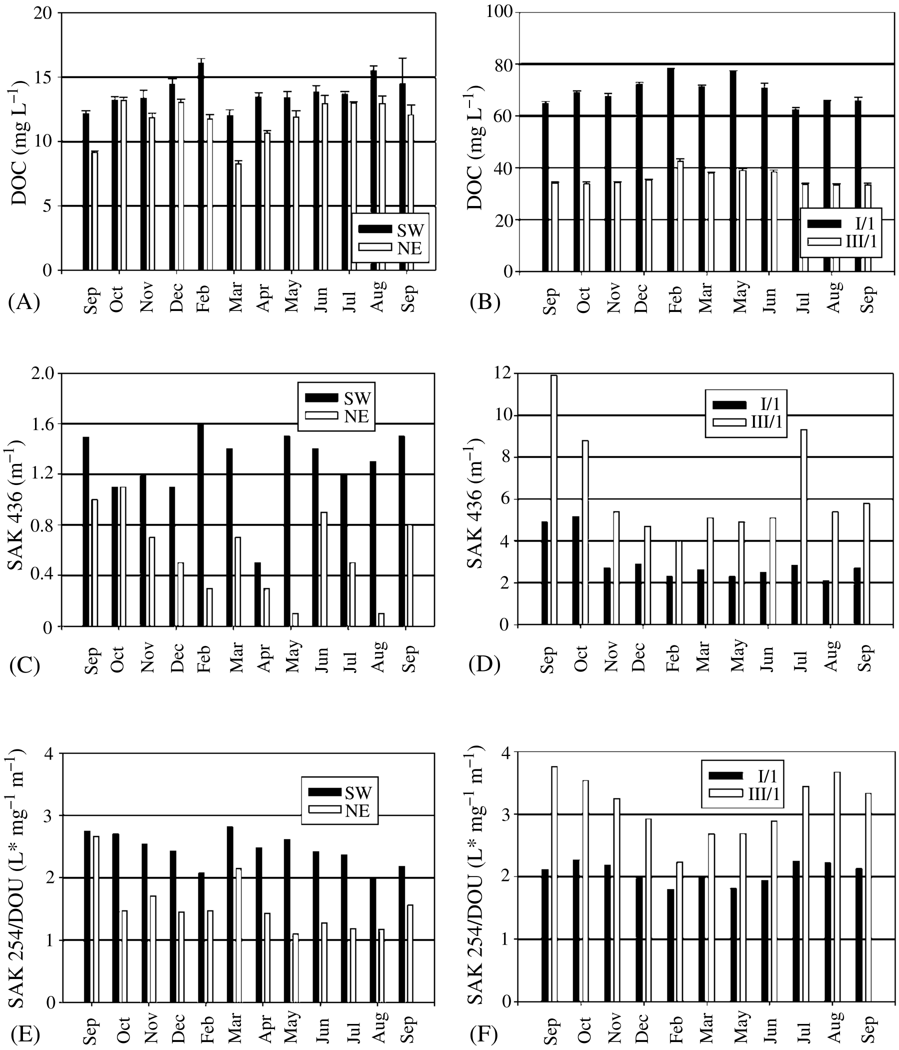

Fig. 7. DOC concentration (A + B) and spectral absorption coefficient (SAK) of the SW and NE compartments and the wells I/1-peat and III/1-peat measured at A 436 nm (C + D) and at A 254 nm (E + F) from September 2000 until September 2001.

tration ranged from 1 to 1.8 mg l^{-1} in the NE, and from 0.6 to 1.1 mg l^{-1} in the SW. However, in comparison, well III/1 (adjacent to the NE compartment) had higher total phosphorus concentration (120.9 to 400.8 μg l^{-1}) but lower total nitrogen concentration (4.6 to 7.3 mg l^{-1}) than well I/1 (adjacent to the SW compartment) with 101.1 to 388.5 μg l^{-1} total phosphorus concentration, and 5.5 to 8.5 mg l^{-1} total nitrogen concentration (Fig. 6(B and D)).

Table 4. Physical and chemical parameters : pH, conductivity, Ca, Mg, total P, total N and DOC of the wells I/1 peat, I/1 sand, III/1 peat and III/1 sand in June 2002.

Well	pH	Conductivity ($\mu S\,cm^{-1}$)	Ca ($mg\,l^{-1}$)	Mg ($mg\,l^{-1}$)	Total P ($\mu g\,l^{-1}$)	Total N ($mg\,l^{-1}$)	DOC ($mg\,l^{-1}$)
I/1 peat	4.36	105	2.80	0.35	159	6.00	64.30
I/1 sand	6.74	436	95.50	0.90	238	3.70	22.40
III/1 peat	5.66	177	20.00	0.40	322	6.50	31.10
III/1 sand	7.15	518	109	4.40	234	4.10	9.70

Comparison between the peat aquifer and the main aquifer in the catchment area

All physical and chemical parameters that were measured differed between the peat aquifer (well I/1-peat and III/1-peat) and the main (sand) aquifer (well I/1-sand and III/1-sand) (Table 4).

The pH of the wells in the peat aquifer was lower than in the wells of the main aquifer: well I/1-peat pH 4.36 and III/1-peat pH 5.66, and in contrast well I/1-sand pH 6.74 and III/1-sand pH 7.15. The conductivity of the wells in the peat aquifer was much lower than in the wells of the main aquifer: well I/1-peat 105 $\mu S\,cm^{-1}$ and well III/1-peat 177 $\mu S\,cm^{-1}$, and in contrast, well I/1-sand 436 $\mu S\,cm^{-1}$ and well III/1-sand 518 $\mu S\,cm^{-1}$. Corresponding to the differences in conductivity concentrations of calcium and magnesium were higher in the main aquifer than in the peat aquifer: well I/1-peat and III/1-peat with calcium concentrations of 2.8 and 20 $mg\,l^{-1}$, respectively and well I/1-sand and III/1-sand with calcium concentrations of 95.5 and 109 $mg\,l^{-1}$ respectively. The magnesium concentrations were much lower than the calcium concentrations; I/1-peat 0.35 $mg\,l^{-1}$ and in III/1-peat 0.4 $mg\,l^{-1}$, and for the main aquifer ^{I}/1-sand 0.9 $mg\,l^{-1}$ and III/1-sand 4.4 $mg\,l^{-1}$.

In contrast to the preceding parameters, the total phosphorus concentration did not show clear differences between the peat and the main aquifer of the catchment area. For the total nitrogen concentrations, similarities between the peat and main aquifer were found. The concentrations of nitrogen in the peat aquifer in well I/1-peat with 6.0 $mg\,l^{-1}$ and in well III/1-peat with 6.5 $mg\,l^{-1}$, were higher than in the main aquifer: well I/1-sand 3.7 $mg\,l^{-1}$ and well III/1-sand 4.1 $mg\,l^{-1}$.

The DOC concentrations in both wells of the peat aquifer were higher than in the main aquifer with significantly high concentration in well I/1-peat compared to well III/1-peat: well I/1-peat 64.3 $mg\,l^{-1}$ and well III/1-peat 31.1 $mg\,l^{-1}$; and in comparison well I/1-sand 22.4 $mg\,l^{-1}$ and well III/1-sand 9.7 $mg\,l^{-1}$.

Discussion

During the genesis of the Lake Fuchskuhle area, the peat aquifer and the main (sand) aquifer developed largely independently. Almost no lateral interactions seemed to have occurred as is evident by their sharply contrasting water chemistry. In the main aquifer, high calcium concentration was consistent with high conductivity (Fig. 5(F), Table 4), an indication of a groundwater flow in Pleistocene sand. The higher calcium concentration in the well III/1 peat than in the well I/1 peat can be explained by the morphology of the area. The catchment of the NE and SE compartment is in contrast to the western compartments directly surrounded by hills, which contain gravel and sandy soil. During high precipitation well III/1 peat might be influenced by water from this sandy soil, whereas well I/1 is not.

Due to the water gradient in the area (Sachse et al. 2001) the groundwater is flowing into the NW and SW compartments (Table 1). In the NW compartment the water balance is nearly balanced. However, the SW compartment received more groundwater than water is flowing out (Table 1). As the groundwater flow transported also DOC and nutrients into the compartments an accumulation of these compounds might occur. For example, in February 2001 coincided with a high groundwater inflow a high input of DOC could be detected (Table 3). At this time the SW compartment had also a higher DOC concentration (Fig. 4), which might correlate to the high groundwater inflow and to the high water colour (Fig. 7(C)). This gives evidence for the influence of the peat aquifer on the chemical conditions of the SW compartments of Lake Fuchskuhle. After February 2001 the inflow and concentration of DOC differed from each other (Fig. 4). The increase of the DOC concentration after March 2001 might be due to enhanced biological activity during spring and summer. Another aspect might be an inhomogeneous peat body with divergent permeability coefficients, which might be responsible for spatial differences in chemical fluxes of DOC and nutrients.

As the NE compartment was not influenced by the peat aquifer (Table 1) the physical and chemical conditions differed to the SW compartment. The significant differences in parameters such as pH, conductivity and DOC characterization gave a clear picture of the heterogeneity of both compartments and their dependence on the catchment area (Figs. 5 and 7). These results support and broad the findings of Sachse et al. (2001) and show very clear, that the water gradient, with its separation into two different ground water aquifers, is responsible for the oligotroph dystrophic character of the SW compartment but not for the mesotrophic character of the NE compartment.

According to the geological investigations in the catchment area of Lake Fuchskuhle, the structure of the peat body developed heterogenously with a meso- to eutrophic fen in the northwest part and a meso- to oligotrophic – acid fen in the southeast part. When investigating flow pathways between land–water interfaces, the interactions between geology and hydrology should be noted.

In the peat aquifer, nitrogen, the most important nutrient for plants (Larcher 1994), was in higher concentration than in the main aquifer. The differences in nitrogen concentration between the peat aquifer and main aquifer could be explained by humification processes, in which nitrogen in the form of oligosaccharides, peptides and amino acids is bound to the high molecular weight structures such as humic substances (Müller-Wegener 1984; Anderson et al. 1989; Schulten & Schnitzer 1995). Since the DOC of the peat aquifer contains high concentration of humic substances (Sachse et al. 2001), nitrogen may be more retained than in the main aquifer. Nitrogen and phosphorus appear in the catchment areas in significantly higher concentrations than in the compartments of the lake, again explainable by stronger humification processes in the peat aquifer. Another aspect is the anoxic conditions in the reduced deeper zones of fens, where anaerobic bacteria might not take part in the nitrogen mineralisation, which, therefore, can result in low mineralisation rates (Koerselman & Verhoeven 1992).

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