Interactions between near-surface groundwater and surface water in a drained riparian wetland

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Abstract Lowland hydrology is characterised by a strong impact of near-surface groundwater which demands an analysis of the interaction between groundwater and surface water. Additionally, a high fraction of agricultural land in lowland catchments is drained and therefore influenced by fast water transport towards discharge systems. A riparian wetland situated in the lowland catchment area “Kielstau” in the north of Schleswig-Holstein, Germany, was investigated. Groundwater, ditch water and river water levels were measured to assess the interactions between these systems. Besides weekly measurements, some data were logged at hourly intervals since September 2005. The results show a high seasonal variability in water levels and flow dynamics in the groundwater as well as in the ditches and the river. Far from the river, at the ditch origin, the interactions in the riparian wetland are characterised by continuous effluent conditions which originate from positive differences in groundwater heads. Close to the river, at the mouth of the ditch, lower differences in groundwater heads are observed. They are partially negative, or change between positive and negative differences and result in a change between influent and effluent conditions.

Key words interaction groundwater–surface water; riparian wetland; lowland catchment

INTRODUCTION Riparian wetlands and flood plains are areas of intensive surface water–groundwater interactions. Such riparian environments are a common feature in the landscape of the North German lowlands and hence, the exchange between river water and groundwater plays an important role in the area.

This exchange can be described in principle by two cases, the effluent and the influent condition. When the groundwater level is higher than the water level in the river, groundwater flows are directed towards the river resulting in effluent flow (exfiltration, Fig. 1) (Winter et al., 1998). In areas where hydraulic gradients are small this results in small flow velocities, although groundwater exchange can still be significant, depending on the size of the interaction zone (Krause & Bronstert, 2005).

When the water level in the river is higher than the groundwater level, river water flows into the groundwater by infiltration causing influent conditions (Winter et al., 1998; Fig. 1). Influent conditions exist likewise, when the groundwater body is separated from the river bed by an unsaturated zone (Winter et al., 1998). Where river and groundwater levels are the same, groundwater flows parallel to the river (Sophocleous, 2002).

Conditions of low river flows are usually characterised by effluent conditions, i.e. groundwater discharge, whereas influent conditions, i.e. infiltration of river water into the groundwater, occur during flooding periods (Liebscher, 1996).

Some rivers exhibit effluent flows in some sections and influent flows in other sections (Winter et al., 1998). Sections of alternating effluent and influent conditions, hence changing flow directions, can also occur, in particular in smaller rivers which are more strongly controlled by local groundwater systems and seasonal influences (Winter et al., 1998; Sophocleous, 2002; Kalbus et al., 2006).

The objective of this study is to understand the water and flow processes in a drained riparian wetland in northern Germany. Of particular interest are the interactions between the groundwater, river and drainage ditches, as well as the temporal and spatial changes in effluent and influent conditions. In this paper, we present the results from the analysis of high-resolution water level data collected at a riparian wetland in the Kielstau catchment.
MATERIALS AND METHODS

Study area

The study site is situated in the lowland catchment area “Kielstau” in the north of Schleswig-Holstein. The catchment is about 50 km² and is a subcatchment of the River Treene. Drainage in the catchment is dominated by the River Kielstau (16 km long) and its tributaries as well as by two lakes. Various smaller tributaries, drainage pipes and open ditches flow into the Kielstau. The drained fraction of agricultural area in the Kielstau catchment is about 38% (Fohrer et al., 2007).

The River Kielstau flows along the southern border of the investigated riparian wetland area toward the west (Fig. 2). This approx. 800-m long river section is about 4 m wide and about 1.5–2 m deep. The Kielstau has been straightened in this section and exhibits a trapezoidal profile. Its annual mean discharge at the catchment outlet (at Gauge Soltfeld) is 0.424 m³/s (1987–2005) (LANU-SH Umweltatlas).

The studied riparian wetland area is about 0.15 km² (approx. 750 × 230 m) and is drained by 11 ditches (Fig. 2). The wetland is used as grassland and is surrounded by arable land with some grassland and/or pasture. The soils are, for the most part, Sapric Histosols (BGR 1999) with the exception of the eastern part, where the dominant soil type is loam and the northwestern part (next to Ditch 1), where sandy soils occur. The area of arable land north of the riparian wetland is also characterised by sandy soil. The 1–2 m thick, medium to highly humified peat of the wetland is underlain by a lime-rich peat clay as was found during a detailed soil sampling survey using a Puerckhauer auger.
The 11 ditches are located perpendicular to the River Kielstau (Fig. 2) and are of different ages, type and length. The investigations focus on three ditches: Ditch 1 has a length of 250 m, a medium depth of 0.65 m, a medium width of 1.36 m and was built in 1999. Ditch 4 is 230 m long, up to 5 m wide, approx. 0.80 m deep and was constructed in 1990. Ditch 8 is 130 m long, has a medium width of 1.19 m and a medium depth of 0.67 m. It was constructed and partly redirected in 1969/1970.

At the end of February 2006, Ditch 1 was dug up for the first time in sections in the centre and at the mouth of the ditch due to a blocked drainage. The drainage pipe, which has its mouth approximately in the centre of the ditch, drains a pond lying north of the grassland area, which takes up the drainage water of the adjacent arable field. This is the only existing drainage pipe in the riparian wetland. Since its construction, no ditch maintenance was accomplished in Ditch 4. Ditch 8 was maintained each year, except in 2005.

**Precipitation**

A temperate, maritime climate is characteristic for Schleswig-Holstein. For the years 1985–2005 the annual average of the precipitation for the station Satrup was about 790 mm (State Agency for Nature and Environment Schleswig-Holstein LANU-SH), but 990 mm for station Flensburg (DWD, 2006). The amounts of precipitation in the investigation area lie between these two stations and this was confirmed by on-site measurements with a tipping-bucket rainfall gauge. During the investigation period deviations occur in relation to the long-time mean values for precipitation.

From 26 December 2005 until 15 March 2006 frequent snowfalls occurred, totalling about 75 mm and covering the study site for 2–3 weeks. Thaw started on the 19 March 2006.

**Data collection**

Topographic information was derived from the DGK5 (German basic map 1:5000, LVA-SH). Soil information was available from the general soil map at a scale of 1:200 000 (BGR, 1999). Land use of the adjacent areas was mapped during the investigation period. The land use management systems, information about age and function of the ditches, as well as possible ditch maintenance measures, were collected via interviews with the farmers.

The water depth of the ditches could not be determined accurately due to the silty ditch base. In order to map the ditch morphology, ditch width, ditch depth, as well as actual ditch water width and ditch water depth were determined in August 2005.

The groundwater well and gauge installations at the study site are illustrated in Fig. 2.

Water levels in the three ditches (Ditches 1, 4, 8) were measured weekly using gauges (Gauges A to F) which were installed at the origin (far-from-river) and at the mouth (close-to-river) of each ditch (Fig. 2). Additional hourly readings were taken by pressure sensors.

Ten groundwater observation wells were installed near Ditches 1, 4 and 8 (Well 1 to Well 10) to study the near-surface groundwater 2 m below surface. The 2 m long groundwater tubes have a diameter of 5 cm. The lower metre was slit with a nominal size of 2 mm and protected against siltation. The wells were arranged in the form of transects next to the investigation ditches at the origin, the mouth and the centre of the ditches, as shown in Fig. 2. Additional observation wells were installed at the border of the riparian wetland (Fig. 2). Weekly groundwater levels were measured at an accuracy of 0.5 cm using an electric light gauge, while hourly readings were taken by pressure sensors.

Water levels of the River Kielstau were measured at the outlet of Ditch 1 (Gauge K) using a pressure sensor and were complemented by weekly manual measurements (Table 1). Hourly precipitation data were collected by a tipping-bucket rainfall gauge at the mouth of Ditch 1.

Groundwater and water levels in the ditches and the River Kielstau were measured at weekly intervals from September 2005 to March 2006 (period A). Afterwards, the sampling frequency was reduced to monthly intervals from April 2006 to June 2007 (period B). Hourly sampling was carried out at four selected measuring points (Table 1).
Table 1 Frequency of measurements at individual measuring points during the intensive period A (September 2005–March 2006) and the less intensive measuring period B (April 2006–June 2007).

<table>
<thead>
<tr>
<th>Measuring points</th>
<th>No.</th>
<th>Measuring period A (interval)</th>
<th>Measuring period B (interval)</th>
</tr>
</thead>
</table>

Fig. 3 Groundwater levels in Wells 1–10 and precipitation data for period A (precipitation values before 25 October 2005 are from Station Satrup (LANU-SH)).

Fig. 4 Ditch water levels (for Gauges A–F), river water levels (Gauge K) and precipitation data for period A (precipitation values before 25 October 2005 are from Station Satrup (LANU-SH)).

RESULTS AND DISCUSSION

Water level dynamics of surface water and groundwater

Groundwater levels, ditch water levels and river water levels for period A are displayed in Figs 3 and 4. The graphs show that the period can be divided into a dry period (September 2005–October
2005) and a wet period (November 2005–March 2006). Several flood events occurred and the highest water levels were observed on the 9 February 2006. The highest water levels during the entire sampling period (A+B) occurred in January 2007 (Fig. 5).

The riparian wetland has surface elevations between 33.85 and 37.0 a.m.s.l., but mostly between 35.0 and 35.5 a.m.s.l., and is characterised by low water table depths. During period A, water levels were on average 0.5 m below the surface. In the neighbouring arable area, the groundwater levels were about 1.5 to 1.7 m below the surface. Considering that peat clay underlies the wetland, this suggests an impounded groundwater table beneath the investigation area.

The trends in groundwater level fluctuations are similar in all wells. Comparison of the hydrographs with precipitation data suggests that groundwater dynamics during the winter period are mostly controlled by precipitation inputs (Fig. 3). Small-scale differences in groundwater level fluctuations, as well as in depth-to-water table, are probably due to the location of the groundwater well within the wetland, and as a result of interactions with water in the ditches and the river. For example, groundwater wells located near the river (e.g. Well 6) show a more dynamic response than those in the centre of the riparian wetland, suggesting a direct hydraulic connection between groundwater and the river. At the slopes of the investigation area (e.g. Wells 9, 10) different dynamics are observed in the dependence of the inflows from the above areas.

Figures 4 and 5 also show that the drainage ditches are characterised by a dry period in summer and by high water levels in the winter. They are fed predominantly by near-surface groundwater and precipitation.

Figure 6 shows hourly groundwater fluctuations in Well 4 (far-from-river). Similar dynamics are found in Well 3 (close-to-river), although the hydrograph is less spiky and peaks are less pronounced. The rank correlation after SPEARMAN for the period 15 December 2005–30 March 2006 of the two hydrograph curves is significant (p<0.05), but the coefficient of correlation of r = 0.63 is rather small compared to the correlation of the weekly measurements (r = 0.903) which smooth the values.

The average increase in groundwater levels in Well 4 is 20.3 ± 12.3 cm (n = 15) and is associated with precipitation events. The maximum water level increase during the investigation period was 39 cm following a period of prolonged precipitation with a total of 23.1 mm rainfall. The lag time between maximum precipitation and maximum water level in the groundwater averages around 19.4 ± 14.7 h.

At groundwater observation Well 3, the medium increase in groundwater level after precipitation events is 4.7 ± 4.0 cm (n = 15). The lag time between maximum precipitation and maximum groundwater levels averages around 40.7 ± 27.9 h. The water level response varies significantly between events depending on the antecedent moisture conditions. But in general, a

![Fig. 5 Hourly ditch water levels (Gauge C) and groundwater levels (Well 4) at the origin of Ditch 4 and daily precipitation data (LANU-SH Umweltatlas) for period A+B.](image-url)
fast response of groundwater level increase on precipitation is supported by the peat clay as a confining layer at a depth of 1–2 m.

Comparing the hourly measurements with the weekly data in Fig. 6 it is obvious that the temporal dynamics of the groundwater system are not sufficiently captured by the weekly data. At least eight peaks are not registered by the weekly measurements during the 7 months (period A). This implies that more detailed data (e.g. hourly) are necessary to understand the groundwater dynamics at the riparian wetland. In addition, the observed lag time between maximum precipitation and maximum water level in the groundwater of about 19 h shows that a daily time step is not appropriate.

**Interactions between groundwater and surface water**

**Interactions between groundwater and Kielstau water levels** The differences between the groundwater levels of the transect at Ditch 4 and the Kielstau water levels is shown in Fig. 7 which illustrates that during period A, groundwater levels are higher than the Kielstau water level. Between the dry period and the wet period no larger differences were determined at Well 4 and Well 5; the values vary between 22 and 44 cm at Well 4 (except for 20 December 2005) and between 16 and 43 cm at Well 5. Well 6 displays the smallest differences. At the beginning of the investigation period, differences of around 9 cm between the groundwater and the river water
levels were observed, but these increased to values between 10 and 30 cm during the wet period. At Well 5 and Well 6, negative differences of up to −11 cm were observed during the floods.

The above results suggest that groundwater levels in the riparian wetland are in most cases higher than those in the river, resulting in effluent conditions. However, during flood events, river water levels rise causing a reversal of the flow gradient from the river into the near-river groundwater and resulting in influent conditions. These can cause contamination in the near-surface groundwater due to entries from surface waters into groundwater.

**Interactions between groundwater and ditch water levels** At the origin of Ditch 1, the groundwater level is higher than the ditch water level during the entire investigation period A. In contrast, groundwater level and ditch water levels at the mouth of the ditch are very similar (Fig. 8). Only after the precipitation period from 6 to 9 February 2006, is the potential difference between the groundwater and ditch water level negative, as the ditch water level (Gauge B) is higher than the groundwater level of Well 3 by 4 cm. The mean differences between groundwater and ditch water level is 10 ± 4 cm between Well 1 and Gauge A, but only 5 ± 4 cm between Gauge B and Well 3.

Similar observations are made at Ditch 4. At the origin of Ditch 4, groundwater levels are above the ditch water levels on all measuring days, with an average difference of 11 ± 8 cm. At the mouth of the ditch, the conditions reverse. The groundwater level during period A is nearly always lower than the ditch water level or similar at the mouth, at several times (Ditch 1) resulting in a negative or no potential difference. The average difference between Well 6 and Gauge D is −6 ± 6 cm.

Fig. 8 Comparison of the water levels of the gauges (A–F) and the corresponding groundwater observations wells (Wells 1, 3, 4, 6, 7, 8) at the origins (far-from-river) and at the mouths (close-to-river) of the Ditches 1, 4 and 8 (period A, September 2005–March 2006).
At the origin of Ditch 8 (far-from-river), the water level distribution is similar to that of the other
two ditches. The groundwater level is higher than the ditch water level during the entire observation
period A except for the flood period on 27 October 2005. The mean difference between ditch water
level and groundwater level is $12 \pm 8$ cm, but the potential differences are often smaller than those of
the other ditches. At the mouth of the ditch, flow conditions change constantly between no flow and
effluent flow and this is reflected in the mean differences of $0 \pm 7$ cm.

For the investigation period A it is found that at the ditch origins (far-from-river) the potential
differences are larger during the wet period than during the dry period (Fig. 9) and that the
differences between groundwater and ditch water level are positive. In contrast, the potential
differences at the mouths of the ditches are smaller than those at the origin and, in the case of
Ditch 4, nearly always negative. The wet period is characterised by more frequent changes
between positive and negative potential differences at Gauge F–Well 8 (Ditch 8).

Fig. 9 Potential differences between ditch and groundwater levels separated to far-from-river ditch
origins (left) and close-to-river ditch mouths (right) for the ditch–groundwater pairs at all three ditches

CONCLUSIONS
A riparian wetland situated in the lowland catchment area “Kielstau” in the north of Schleswig-
Holstein, Germany is characterised by near-surface groundwater with low depths to water table.
Dynamics of near-surface groundwater are generally controlled by precipitation and, close to the
river, also by river water level.

A fast response of groundwater level increase during precipitation events is supported by the
peat clay as a confining layer situated at a depth of 1–2 m below the surface. The groundwater
observation well far from the river (Well 4) shows a higher increase in groundwater levels after
precipitation events and a shorter lag time between maximum precipitation and maximum
groundwater water level than the well close to the river (Well 3). The water level response varies
greatly between events depending on the antecedent moisture conditions and water discharge, and
solute transport with it is in relationship with the position in the wetland.

The high groundwater level dynamics at Well 4 can be registered in each case only
insufficiently with the weekly measurements compared to the hourly data set. The observed lag
time between maximum precipitation and maximum water level in the groundwater is about 19
hours and shows that a daily time step is not appropriate. It is advisable to collect measurements at
smaller time intervals in order to better understand the groundwater dynamics at the wetland.

The interactions between groundwater and surface water in the riparian wetland are
characterised in most cases by effluent conditions with higher groundwater than river water levels;
influent conditions occur only during flood events. Furthermore, the distance to the river is
important for a hydrological separation within each ditch. At the origins of the ditches effluent
conditions arise; in contrast at the ditch mouths changing situations between influent and effluent
conditions take place. Therefore, solute entries are not one-directional but entries from surface waters into the near-surface groundwater occur during floods and can cause contamination. Knowledge about the interaction of water levels is the basis for the assessment of solute transport and flow conditions in drained wetlands have to be considered when establishing management plans. Therefore, understanding these flow processes will help to estimate the contribution of such riparian wetlands to the overall water balance and the water quality in river catchments.

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