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REPORT

Retention of agricultural diffuse pollution through constructed wetlands - A case study in Iffendic (France)

Project acronym: AQUISAFE 1 Extension

by

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for

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Title

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Abstract

The Aquisafe project aims at mitigation of diffuse pollution from agricultural sources to protect surface water resources. The first project phase (2007-2009) focused on the review of available information and preliminary tests regarding

(i) most relevant contaminants,

(ii) system-analytical tools to assess sources and pathways of diffuse agricultural pollution,

(iii) the potential of mitigation zones, such as wetlands or riparian buffers, to reduce diffuse agricultural pollution of surface waters and

(iv) experimental setups to simulate mitigation zones under controlled conditions.

The present report deals with (iii). It presents monitoring results on a constructed wetland, situated in the French community Iffendic, on the banks of the River Meu. The wetland was built by the local community, primarily as a flood control and nitrate retention measure. It is fed by drainage inflow from a small agricultural catchment of ~20 ha. It is constructed as a serial system of two vegetated infiltration ponds and infiltration ditches. Direct surface flow to the River Meu can occur at high water levels through an overflow from the second pond.

The monitoring showed that inflows from drainage ditches in Brittany are likely one of the major sources of nutrients to the rivers of the region. As a result the constructed (though near-natural) wetland between a drainage ditch and the River Meu near Iffendic follows a very sensible approach. As planned in the design, subsurface flow paths were shown to flow through the wetland towards the River Meu. However, the share of infiltration turned out to be less than 1 % of the total water volume, because of low soil permeability and high flow events after rain storms. As a result the major share of the drainage inflow flows through the two basins before directly overflowing to the River Meu. Finally about 20 % of the water is retained in the system.

Despite the suboptimal wetland hydrology, up to 41 % of nitrates and 16 % of phosphorus are retained in the wetland. These numbers are reached most probably by denitrification and plant uptake in the two basins. The retention could probably be further improved by (i) enlarging the basins, (ii) increasing the residence time in the drainage ditch (e.g., by installing small cascades) or (iii) by filling the drainage ditch with organic substrate, such as straw or bark mulch.

Apart from the benefit in nutrient retention, the constructed wetland also shows a significantly increased plant bio-diversity compared to the former pasture. The reason for the higher plant diversity is the heterogenic habitat (ponds, hedges, etc.) and not oligotrophication, since the wetland is fed by agricultural drainage.

The significant retention of agricultural pollutants, as well as the increased bio-diversity in the constructed wetland in Iffendic stress the potential of such mitigation systems.

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1 Background of the study

The Aquisafe project is a cooperation of the Indiana University Purdue University Indianapolis (IUPUI, USA), the German Federal Environmental Agency (UBA, Germany) and the Berlin Centre of Competence for Water (KWB, Germany). Aim of the project is the development of a scheme for natural mitigation zones to protect surface waters from diffuse pollution. In particular, key contaminants, applicable modelling tools and potential substance removal by constructed wetlands or riparian zones are being studied. Within these frameworks, one case study was chosen on an existing constructed wetland close to Iffendic in Brittany, France (see map in Figure 1).

Brittany was chosen as a site for case studies, as it is the number one agricultural region in France. Intensive agricultural activities are responsible for a severe diffuse pollution problem in surface waters. For instance, several rivers, which are used for drinking water generation, exceed the EU raw water regulation threshold of 50 mg NO_3/L for nitrates (NO_3) (EU directive 75/440/EEC). As a result, Veolia Water, the main sponsor of the Aquisafe project, will have to shut down water works, e.g., on the Ic River.

Figure 1: Location of the wetland within Brittany

The monitored wetland was constructed in 2002 in the floodplain of the River Meu, as a compensation measure by the community of Iffendic. Apart from flooding events the wetland is mainly fed by an agricultural drainage ditch. The design aims at increasing water retention to (i) retain water during flooding of the river and (ii) remove nitrates from the agricultural drainage water before it enters the river. The constructed system of ditches and basins should maximize infiltration of drainage water. A secondary aim of the wetland construction is its potential as a diverse habitat of fauna and flora, thus increasing the overall bio-diversity of the river stretch.

The following report focuses on the analysis of monitoring data from the constructed wetland in Iffendic to assess its nutrient retention capacity (chapter 3). After an introduction to the site (chapter 2) a detailed analysis of hydrological pathways (3.1) and the retention of nutrients along these pathways (3.2) are presented. In addition the wetland biodiversity (chapter 4) was assessed within this study.

2 Site description

The Iffendic wetland is located in Brittany, in the department of Ille-et-Vilaine, in the alluvial plain of the Meu River on its right bank (Figure 2). The constructed wetland has been monitored since 2004 in order to assess mitigation of diffuse pollution to improve surface water quality.

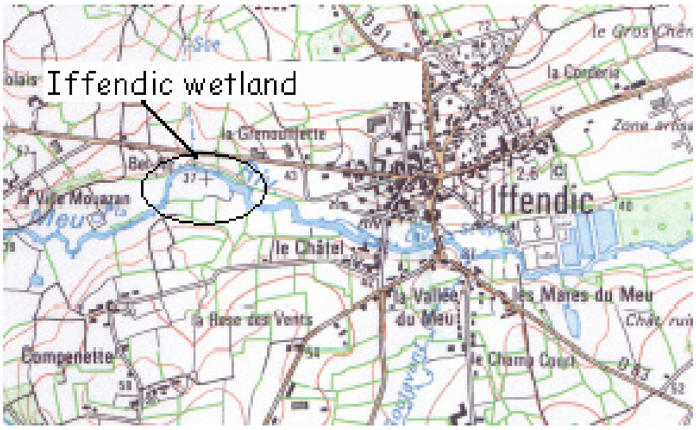

Figure 2: The Iffendic wetland location

The surface of the catchment of the constructed wetland is roughly 20 ha. It consists almost exclusively of farmland, with dominance of corn and cereal cultivations (Figure 3). The drainage water (a part is tile drained) flows into a system of ditches and finally enters the constructed wetland from the South. The wetland has an approximate size of 2 ha. Thus the wetland covers a comparably high ratio of roughly 10 % of its catchment.

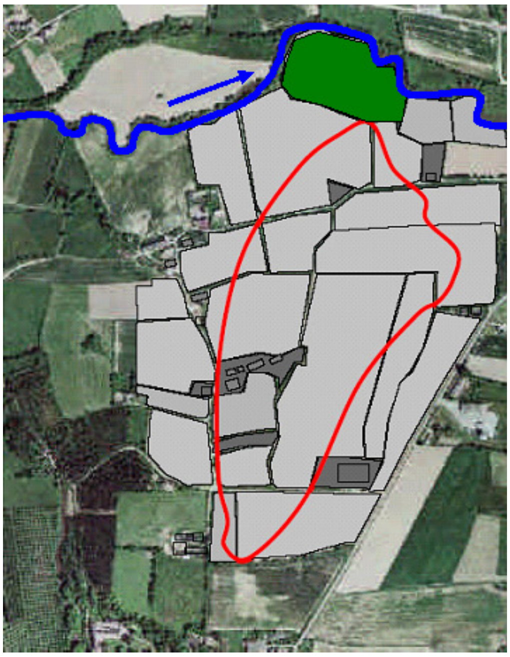

Figure 3: Aerial picture with the constructed wetland (in green), its estimated catchment (red line) and the River Meu (blue line) (*from the SEEGT, 2005a*)

In Figure 4, a schematic plan of the constructed wetland is shown. The infiltration basins 1 and 2, which are connected by an overflow, are supplied by agricultural drainage inflow from the entry ditch ("fossé"): the drainage inflow enters Basin 1. Basin 1 has two overflows, one to ditch 1 (39,539 m asl) and one to basin 2 (39,359 m asl). Consequently, at rising water level water will first overflow to basin 2 and then to ditch 1. Basin 2 has three overflows, two to the ditch 2 (39,237 m asl and 39,254 m asl) and one to the river Meu (39,439 m asl). Thus for basin 2 the water will overflow first to the ditches and only as a last measure to the River Meu.

In the topographic map in Figure 5, we observe a general decrease in elevation from the wetland towards the river. Apart from the two basins there is a slight depression, a natural wetland, between the two basins. Apart from this "third" basin the two man-made basins are separated topographically by a small hill. As the photographs in Figure 6 indicate, the basins are unsealed, but simply dug and left to natural vegetation. Whereas grass cover is mown regularly between the basins, vegetation within the basins themselves is not removed.

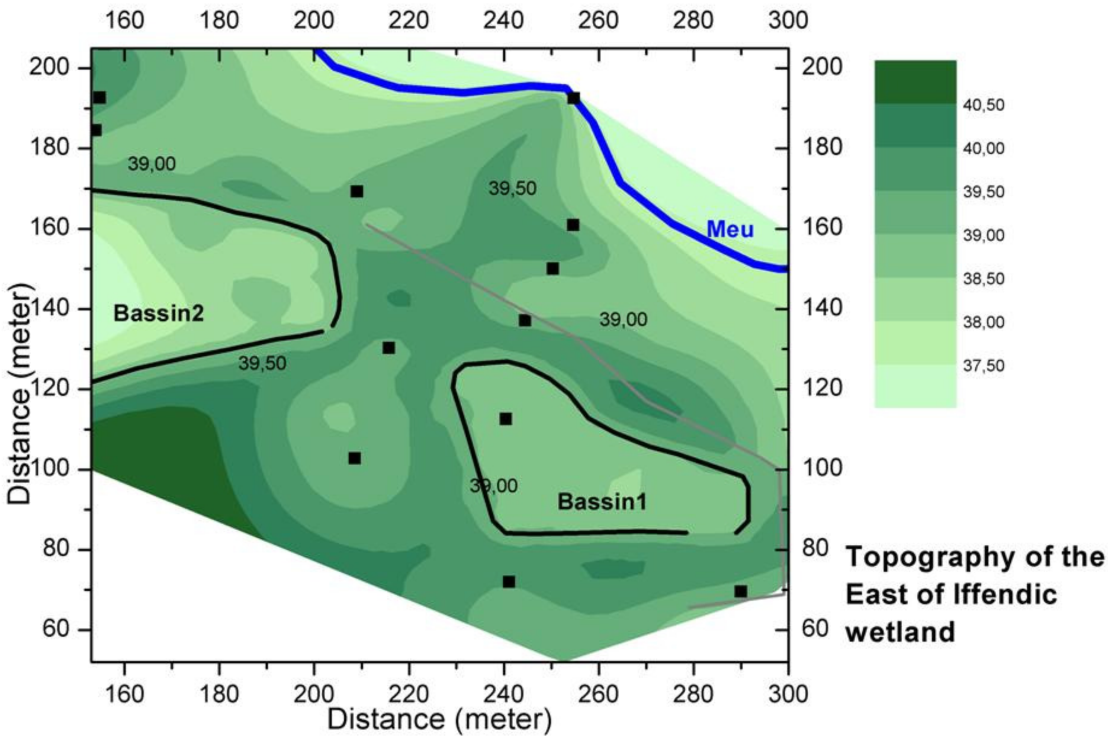

Figure 5: Topographic contours of the west part of the wetland

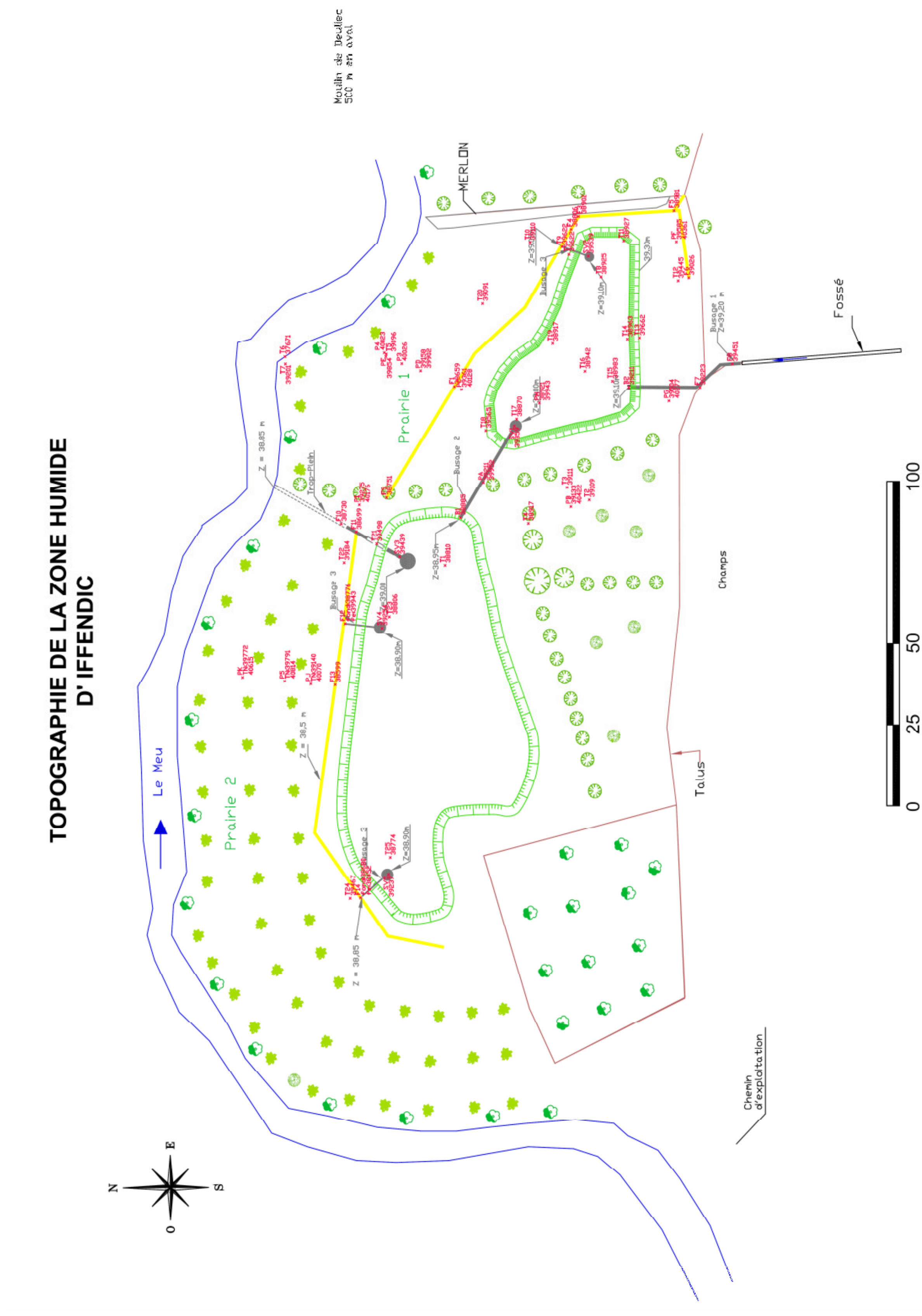

Figure 4: Schematic overview of the wetland in Iffendic *(from SEEGT).*

The river Meu is regulated downstream from the wetland.

Geological cores done close to the wetland and the available (coarse) geological map help to understand the geological context. As in most of the region, the area of the wetland is dominated by schist rocks.

In addition topsoil (depth 0 to 1 m) samples from the wetland were analyzed (one sample next to each piezometer), indicating low permeable soils with high clay contents between 23 and 39 % (average clay content from 17 samples = 30 %).

The ditches, as well as the basins are not cut to the underlying bedrock, but are in the topsoil. As a result they are expected to be mostly on clay-rich solis with low permeability.

Figure 6: First basin in July and December 2007.

3 Nutrient retention in the wetland

3.1 Materials and methods

3.1.1 Hydrology and hydrogeology

Twelve piezometers are installed in the wetland area. Some of them are equipped with pressure sensors, which permit a continuous record of groundwater levels. Pressure sensors are also placed in basin 1 and in the river Meu (Figure 7). All pressure sensors consist of two sensors, one which measures pressure in the water and one which measures atmospheric pressure for correction purposes. In addition, water levels are measured manually twice a month during field campaigns.

Drainage inflow to basin 1 is registered in a pipe, which connects the entry ditch ('fossé') with basin 1. The instrument calculates inflow via pressure sensor measurements for water level and simultaneous ultrasonic (Doppler) measurements of flow speed.

In a topographical survey, elevations of piezometers and further reference points have been measured in meters above sea level.

Rain data are available from a national meteorological station in Bléurais located seven km from the wetland

The continuous water level measurements have to be corrected (i) in respect to the top of the piezometers as the exact location of the sensor in the piezometer is not known and (ii) for sea level elevation to be comparable among each other. The water levels from piezometers were corrected with manual measurements from campaigns to reach (i), as well as measured elevation for (ii) (Example for piezometer A in Figure 8). The precision of the manual measurements are estimated to be ~0,5 cm. As the precision of pressure sensors and the elevations is significantly higher, the precision of the corrected levels can be assumed to be ~0,5 cm.

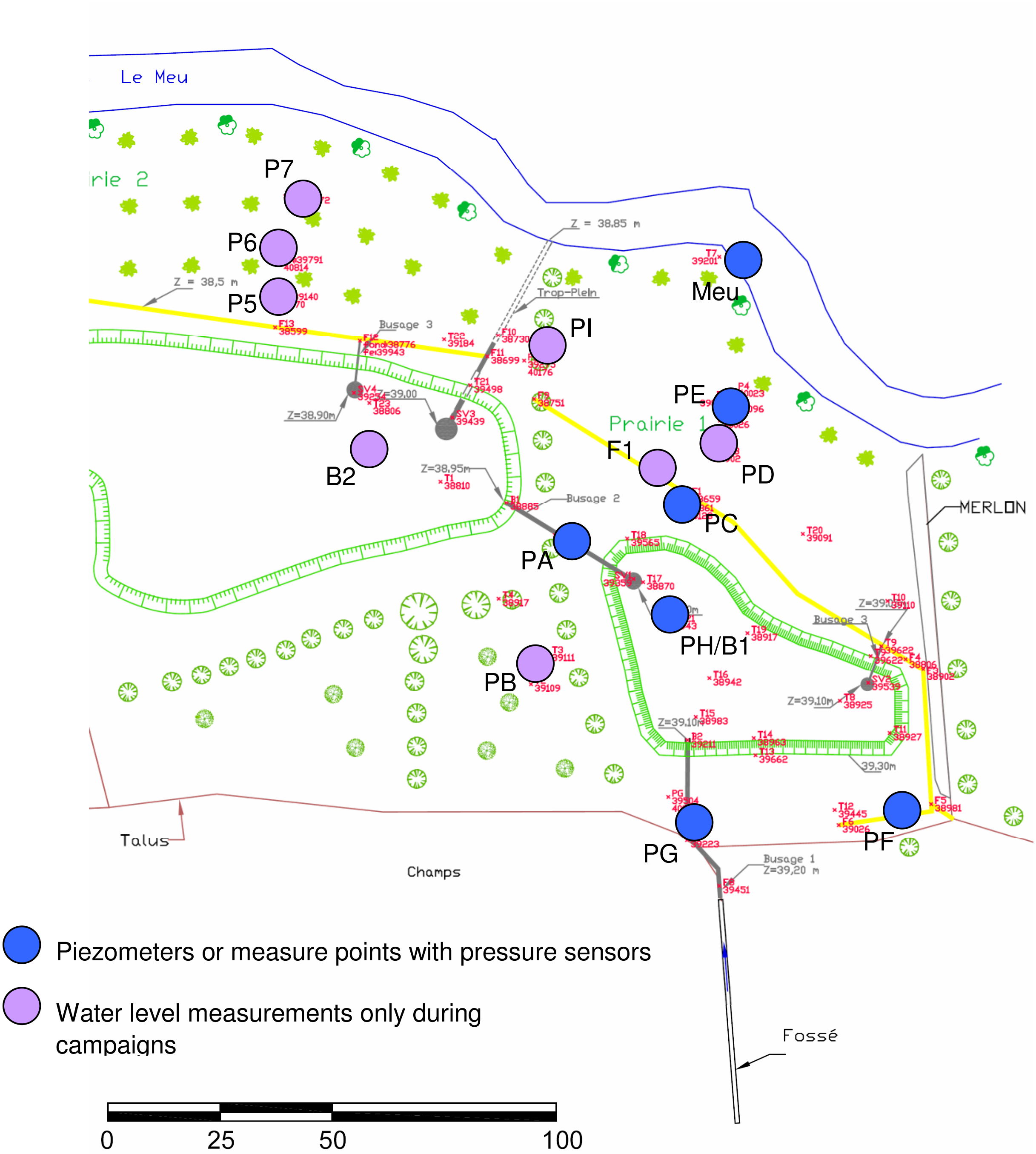

Figure 7: Location of the different points of water level measurement (P indicate piezometers, B basins, F ditches and Meu the River Meu). Scale is in meters. All the blue and purple points were sampled at each campaign. In addition, pressure sensors were installed at all the blue points.

Apart from the soil samples (see above) direct infiltration experiments were performed with a permeameter in two sites of the wetland. The experiments resulted in K_f of $7{,}5 \cdot 10^{-7}$ and $1{,}9 \cdot 10^{-6}$ m s^{-1}, in basin 1 and next to piezometer PC respectively (see map in Figure 7). These values confirm the low permeability expected from grain size analysis.

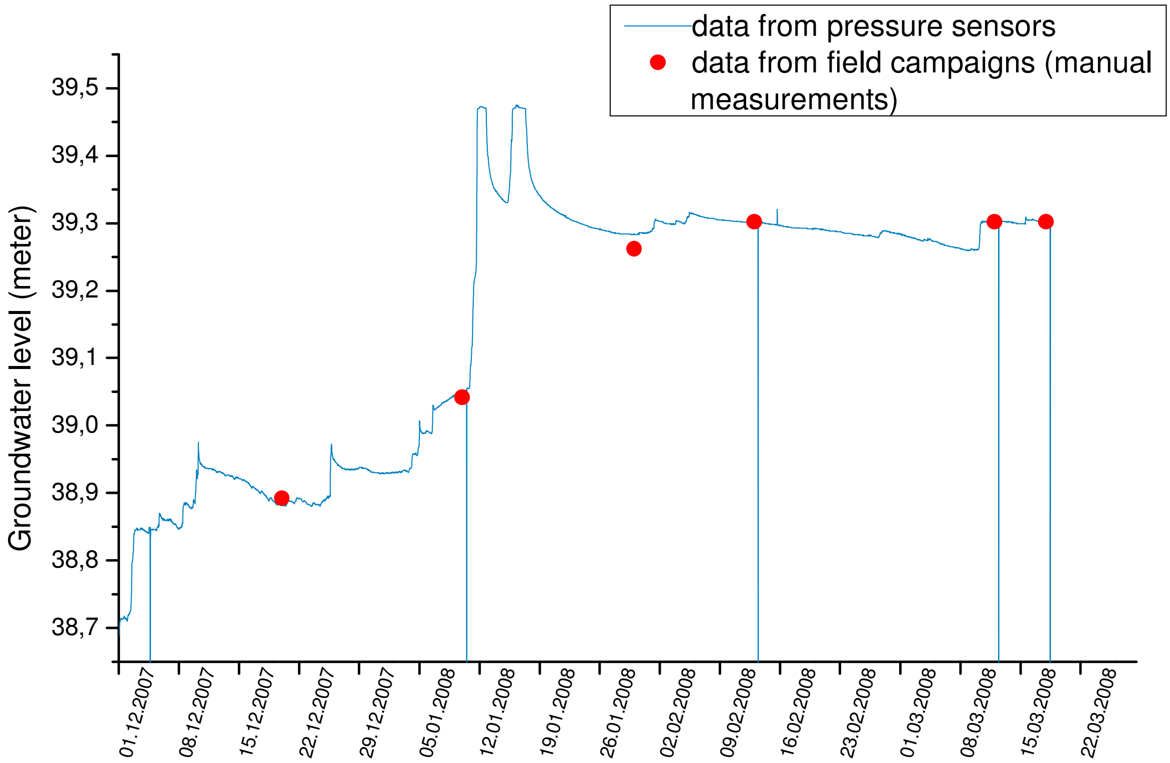

Figure 8: Water level correction (with a constant offset) for the piezometer A to meters asl

3.1.2 Water quality

Bimonthly water samples were taken from December 2007 to May 2008 from the entry ditch, basin 1 and 2, the two ditches within the wetland, the Meu and piezometers. Grab samples from surface water were taken in plastic bottles. For the piezometers samples were taken after manual pumping resulted in constant values on the multi-parameter probe (see below).

Chemical analyses have been realized twice a month at the Centre d'analyse environnmentale, grand ouest (CAE), following each sampling campaign. Nitrates, Ammonium and partly orthophosphates have been measured on samples from piezometers and surface water by ion chromatography. In addition total phosphorus was measured (after digestion to orthophosphates) for surface water samples. The relative measurement error, assessed by CAE through inter-laboratory exercises, is 15 % for nitrate, total phosphorus and orthophosphate, and 20 % for Ammonium.

In addition standard parameters conductivity, pH, redox condition, temperature, and dissolved oxygen were measured in situ during campaigns with a multi-parameter probe.

Results are shown as box plots. As there are different forms of box plots in use, Figure 9 shows the definition used in this report.

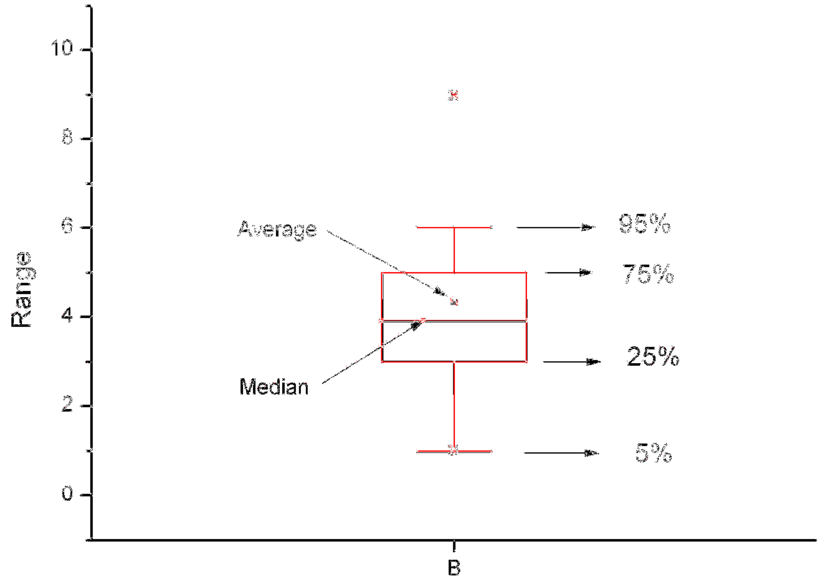

Figure 9: Box plot representation. The percentages indicate the repartition of measurements in the data series. The upper and lower stars are the maximum and the minimum values.

3.2 Hydrology of the site

3.2.1 Hydrogeological pathways

Temporal evolution of groundwater level

Figure 10 presents the continuous water level evolution from December 2007 to May 2008 in the different piezometers, the basin 1 and the Meu (see Figure 7). In the top part, concurrent daily precipitation is shown.

Globally, the variations are very similar in each piezometer, even if the amplitudes of the level fluctuations depend on their location within the wetland. Several aspects about the hydrology of the wetland can be observed:

In January, two flooding situations from the river are clearly visible with two major peaks in all the piezometers. They are the result of the flooding of the River Meu. The maximum level of the flood was not measured by most piezometers, because the sensors measuring atmospheric pressure (see methods) were also submerged, which results in a suspension of the measurement. However, based on piezometer A maximum flooding level of ~40,2 m asl can be found, which indicates that the total wetland was submerged by at least 0,7 m. Before the flooding groundwater levels in all the piezometers follow precipitation patterns. After the flooding fluctuations are reduced, probably as a result of saturation.

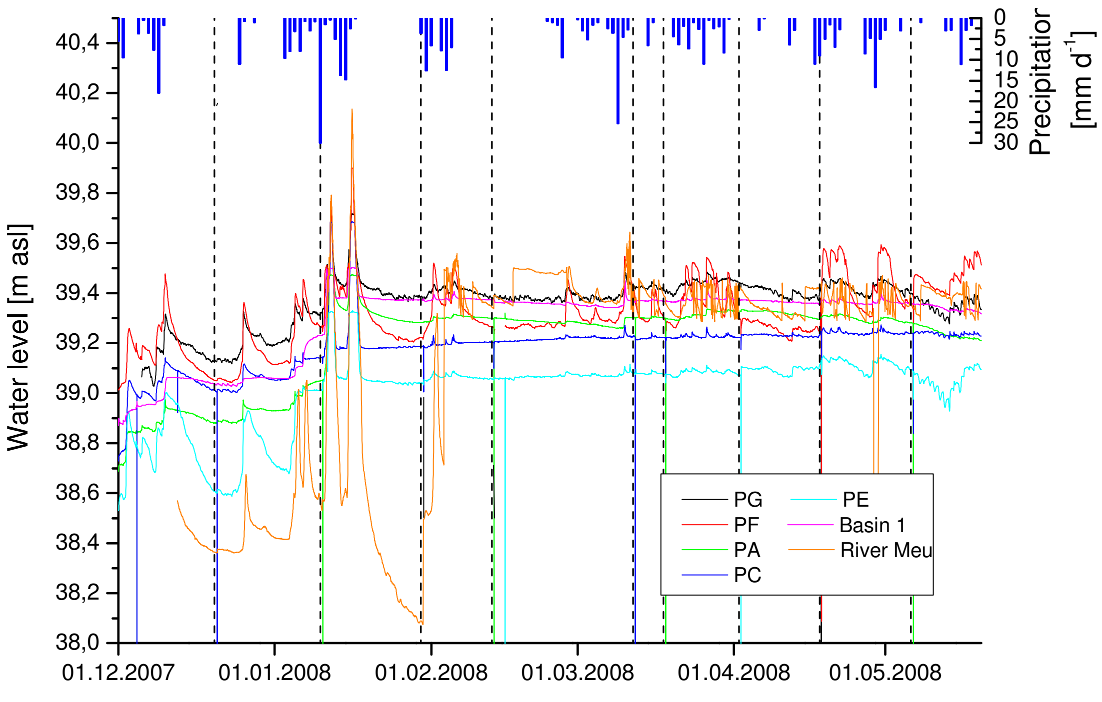

Figure 10: Water table elevation in meters above sea level for the Meu, basin 1 and piezometers A,C,E,F,G. Precipitation is shown in mm per day. Dashed lines indicate dates of campaigns

Looking at the water level in the Meu, strong fluctuations are visible. The reason is a weir downstream of the wetland, which is always closed except between December and January, because of flood control. Thus two hydraulic situations are distinct in this graph: (1) Until the end of January, the level of the Meu is lower because the gate is open. (2) After the closing of the gate in the end of January, the level of the Meu increases by about one meter.

Contours of groundwater level

To get a better spatial understanding of the relationship between the river and the wetland, contour plots have been established for each measurement campaign (see dashed lines in Figure 10), because during campaigns water levels are available for all the piezometers (see Appendix 1 for full set of contour plots).

The horizontal and vertical axes represent East-West distances and North-South distances in meters, respectively. The level of the Meu is not verified, but estimated from flooding. Small inconsistencies, e.g., when basins are shown with two different water levels, are the result of automated interpolation. The right bank of the River Meu (bold blue line), the banks of the two basins (bold black lines) and the ditch 1 (grey line) are indicated in all the contour plots for orientation. Moreover piezometers are shown as black squares.

Among these different piezometric maps (see Appendix 1) two main cases can be distinguished according to their hydrological conditions.

(i) Groundwater flow from the wetland aquifer to the river Meu. This hydraulic situation is exemplified in Figure 11 a. It is observed at low levels of the Meu River until end of January and after rain storms, such as on 12/03/08.

(ii) Possible groundwater pathway from the River Meu to the wetland. This hydraulic situation is exemplified in Figure 11 b. During such conditions water will probably flow towards the centre of the wetland, both from the Meu and from the basins. It has to be noted that situation (ii) is less clear, since there are no piezometer levels available between the river and the water table depression visible in Figure 11 b. However, since the water level in the river is significantly higher than in the piezometers and soils close to the river were not distinguishable from general wetland soils, it is expected that groundwater flow from the river into the wetland is possible.

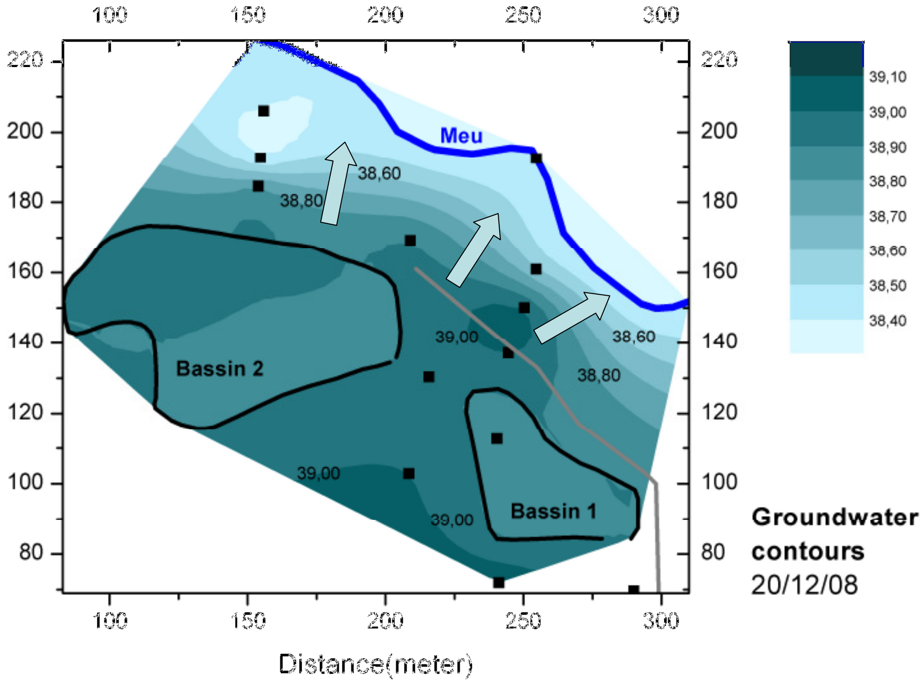

Figure 11 a: First case: the groundwater flows is from the wetland to the river

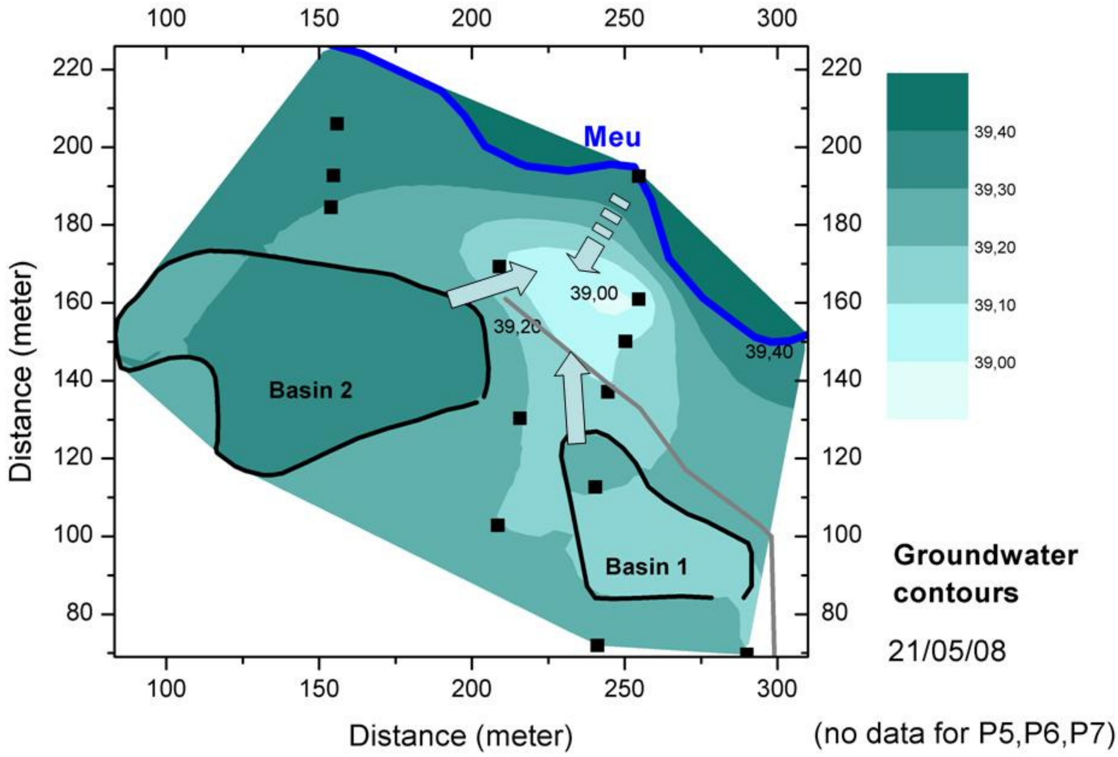

Figure 11 b: Second case: the groundwater flows from the river Meu to the wetland

The water table contours give a general idea of the groundwater pathways based on twelve piezometers and three surface measurements. Given the limited number of points real flow conditions may be different from those shown in interpolated sections.

For the whole period, the average gradient can be calculated between the Meu and the basin 1. The average level difference between basin 1 and the Meu River over the whole measured period (N = 8343) resulted in +0,28 m, indicating a predominant tendency of flow towards the river. The average gradient (i) can be calculated by dividing this value by the distance of ~50m between these points:

$$i = 0{,}28 \text{ m} / 50 \text{ m} \rightarrow \quad i = 0.006$$

3.2.2 Water balance

To get a good view of Iffendic hydrology as well as substance retention, it is essential to make an estimation of the fraction of water which follows a surface versus sub-surface pathway. A simplified water balance of this hydraulic system can be defined by equation (1), with the assumption that there is no variation in the water stock in the wetland on an annual basis (Figure 12):

$$\Delta Q = Q_{in} - Q_{overfl} - Q_{evap} - Q_{infil} = 0 \tag{1}$$

where Q_{in} [m^3 yr^{-1}] is the drainage inflow, Q_{overfl} [m^3 yr^{-1}] is the direct flow to the Meu via the two basin overflows, Q_{evap} [m^3 yr^{-1}] is the sum of evaporation and evapotranspiration, Q_{infil} [yr^{-1}] is the infiltration, ΔQ [m^3 yr^{-1}] is the change in water content of the wetland.

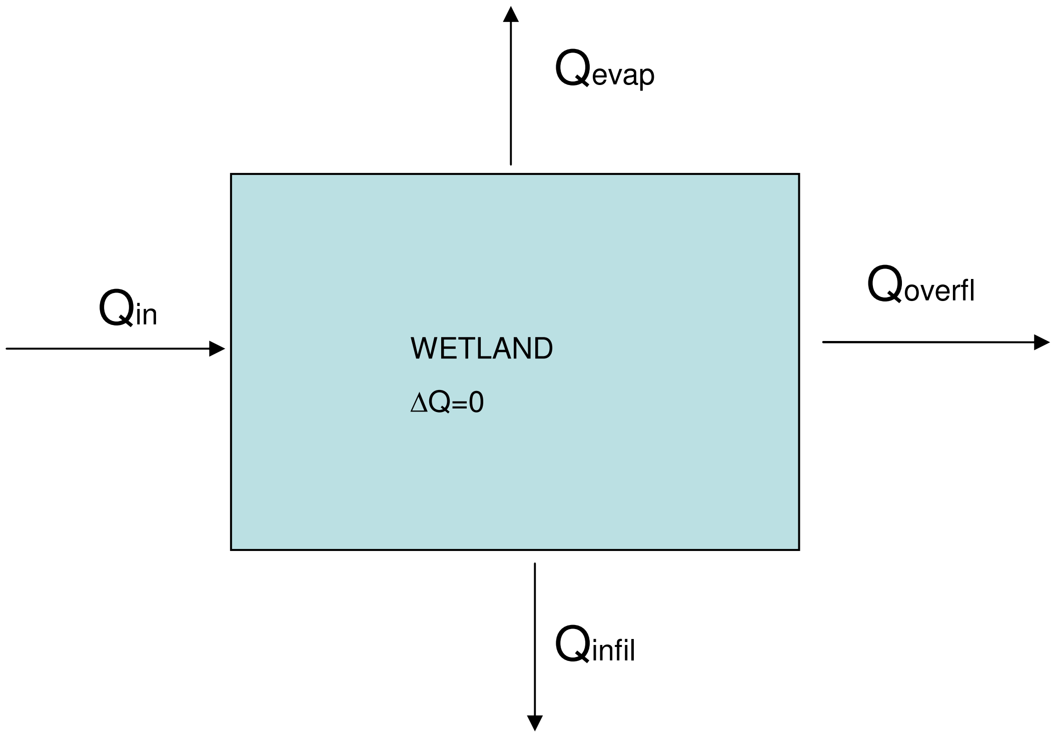

Figure 12: Schematic water balance of the wetland.

Infiltration

The infiltrated volume can be estimated using the equation of Darcy:

$$Q_{infil} = K_f \cdot A \cdot i \qquad (2)$$

where K_f [m/s] is the hydraulic conductivity, A ~1000 m^2 is the area perpendicular to subsurface flow, based on an estimated depth of shallow groundwater of 5 m and a length across the two basins of 200 m, i ~0,006 [-] is the hydraulic gradient, estimated in section 3.2.1.

Infiltration experiments resulted in a K_f values between $7{,}5 \cdot 10^{-7}$ and $1{,}9 \cdot 10^{-6}$ m s^{-1}. Grain size analysis can be used to verify the order of magnitude of these results using the following relationship:

$$K_f = c \cdot (D10)^2$$

where c = 0, 0046 · 10^{-3} [1/(mm · s)] and 10 % of the soil particles have a grain size smaller than D10 [mm]. The results of soil analyses from the wetland were used to do grading curves to deduce D10. However, about 30 % of grains were smaller than the smallest analyzed size of 0,002 mm. As a result we assumed a maximum of D10= 0,002 mm. Using this maximal D10 resulted in $K_f = 0,0046 \cdot 0,002^2 \approx 1,84.\ 10^{-8}$ m s^{-1}. The K_f from soil analysis is lower than the result of infiltration experiments. This can be explained, as the grain size approach does not include the effect of roots and macropores. Still it confirms the order of magnitude of the experimental measurement.

Using the experimental K_f values, equation (2) results in an infiltrated volume of water Q_{infil} between 132 and 336 m^3 yr^{-1}.

Although infiltration experiments are more representative than soli analysis, they do not cover potential preferential flow paths. Preferential flow paths cannot be ruled out completely, though collected soil samples were very homogenous. However, very high gradients in groundwater levels, which persist for long time periods indicate that groundwater flows are indeed very slow. For instance, piezometer PE, which is situated ~10 m from the river (Figure 7) shows a gradient to the river > 0.5 m for more than 20 days in January/February 2008 (Figure 10).

Drainage inflow

Although topsoil is typically followed by bedrock in the area, no deep drilling has been made on the site and consequently deep groundwater flow from the agricultural area to the River Meu is possible. However, since the two basins and the ditches are in the topsoil with low permeability no major groundwater inflow into the wetland is expected. As a result, we conclude in the following that the water from the agricultural fields enter the wetland only via drainage inflow. Figure 13 represents the cumulated flow measured in the entry ditch from 01.01.2008 to 21.05.2008. Thus Q_{in} can be estimated as ~53 000 m^3 for this time period. The steeper part shows sections of maximum inflow. The structure of the cumulated line indicates that more than 50 % of the inflow occurred over a short period of a few days.

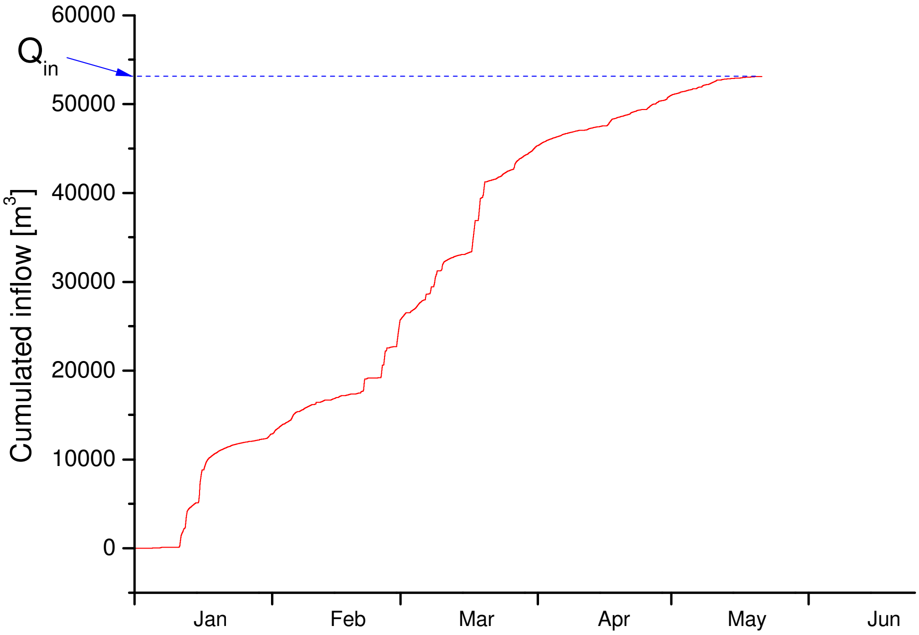

Figure 13: Culmulated flow measured at the entry of the wetland

Over the observed period a total precipitation of ~383 mm was measured. For the 20 ha catchment of the wetland this translates into a total volume of ~77 000 m^3. Thus, roughly 2/3 of the precipitation on the catchment ends up in the wetland. This is a sensible order of magnitude, considering (i) that the fields in the catchment are mostly drained and (ii) that major rainfall occurred outside the vegetative period.

Overflow to the River Meu

The volume of the two basins was estimated as 2 500 m^3. So it is possible to calculate the overflow of the two basins based on the measured inflow, if we neglect evaporation (Figure 14, upper panel). Concurrent level measurements in basin 1 (Figure 14, lower panel) allow to double check, whether the water really did overflow, at least from basin 1 to basin 2. Both level and inflow measurements indicate an onset of overflows, shortly before the flooding of the River Meu. Moreover two periods v3 and v4 of low inflow, where evaporation or other losses prevent overflows, can be distinguished in Figure 14. The volume which corresponds to the periods without overflow is v3+v4 ≈ 6 300 m^3.

The volume, which left the basin through the overflow can be now calculated as the difference between total inflow, the basin volume and “evaporated” volume:

$Q_{overfl} \approx 50000 - (2500 + 6300) = 41200\ m^3$

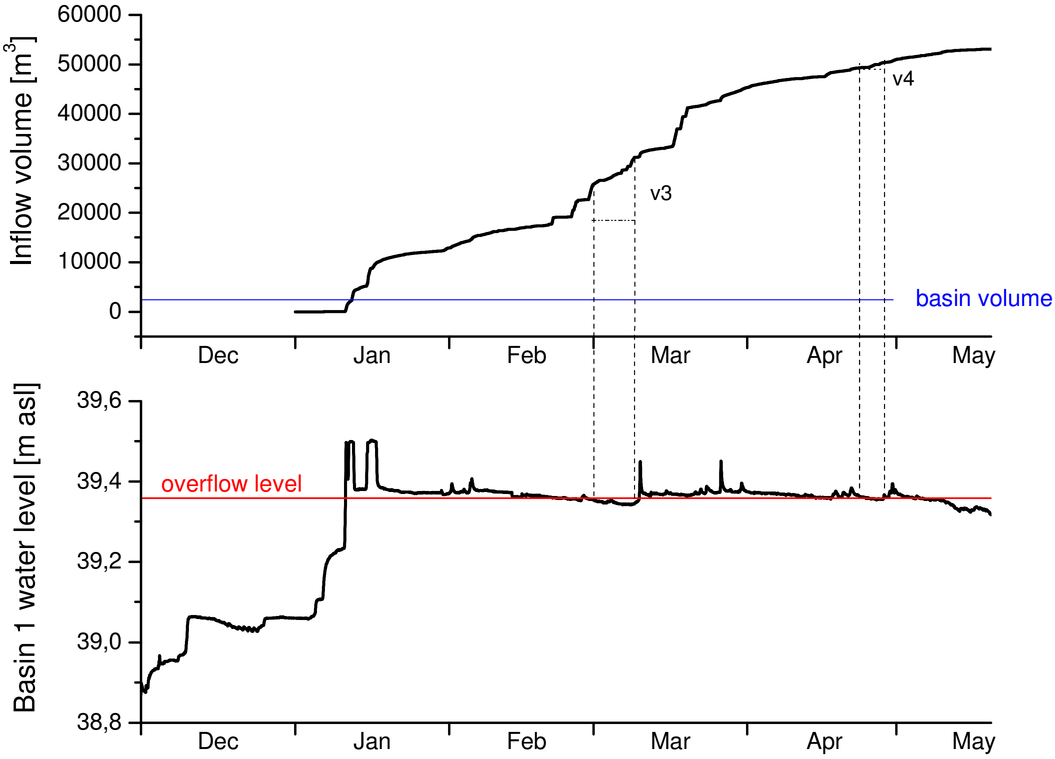

Figure 14: Inflow volume [m^3] to the wetland (upper graph) and water level [m asl] fluctuations in basin 1 from January to May 2008

Evapotranspiration

Evapotranspiration from equation 1 yields:

Q_{evap} ~ 11 500 m^3

The total surface of the wetland is S_{tot} ~30 000 m^2 (200m x 150m), whereas the basins cover an area of S_{basin} ~10 000 m^2. As water can overflow to the total wetland via ditches, the relevant area of evapotranspiration is probably in between. The estimated volume of evapotranspiration and evaporation from the estimated surface area is therefore from 380 to 1 100 mm for the observed 5-month period (~Q_{evap} / S). The order of magnitude compares well with an other case studies from Brittany (Montreuil and Merot, 2006), which reported an annual Q_{evap} of around 700 mm yr^{-1}. In comparison our value may be slightly too high, although the 11 500 m^3 includes water, which is retained in the wetland and will evaporate later in the year.

The overall water balance is shown in Table 1. It is clearly evident that only a small fraction of the drainage inflow infiltrates in the wetland (< 0.6 %). The main path of inflowing water goes directly to the river via the storage basins (78%). The other 22% are retained by plant uptake and evaporation from the basins and other flooded parts of the wetland.

Water balance	[m^3 yr^{-1}]	[% of Q_{in}]
Q_{in}	53 000	100%
Q_{overfl}	41 200	78%
Q_{evap}	11 500	22%
Q_{infil}	< 336	< 0.6 %

Table 1: Estimated water balance for the wetland

It is important to check whether 2008 was a particular climatic year. The lower panel in Figure 15 shows a comparison of the precipitation observed from January to June 2008 with the same period for other years, where precipitation data were available for the station in Bléurais. The comparison indicates that the first half of 2008 was indeed wetter than average. Thus the water overflowing during the rainy season may be above average in the above analysis. However 2008 is by no means extreme with even wetter 2001 and a similar order of magnitude in 2000 and 2007. If we compare the seasonality of precipitation (upper panel in Figure 15), the observation period follows general trends in other years, but again above average. However, significant overflow would be expected even if Qin is only 50 % of the 2008 value. As a result we can conclude that important shares of water will pass the wetland via overflow in any year.

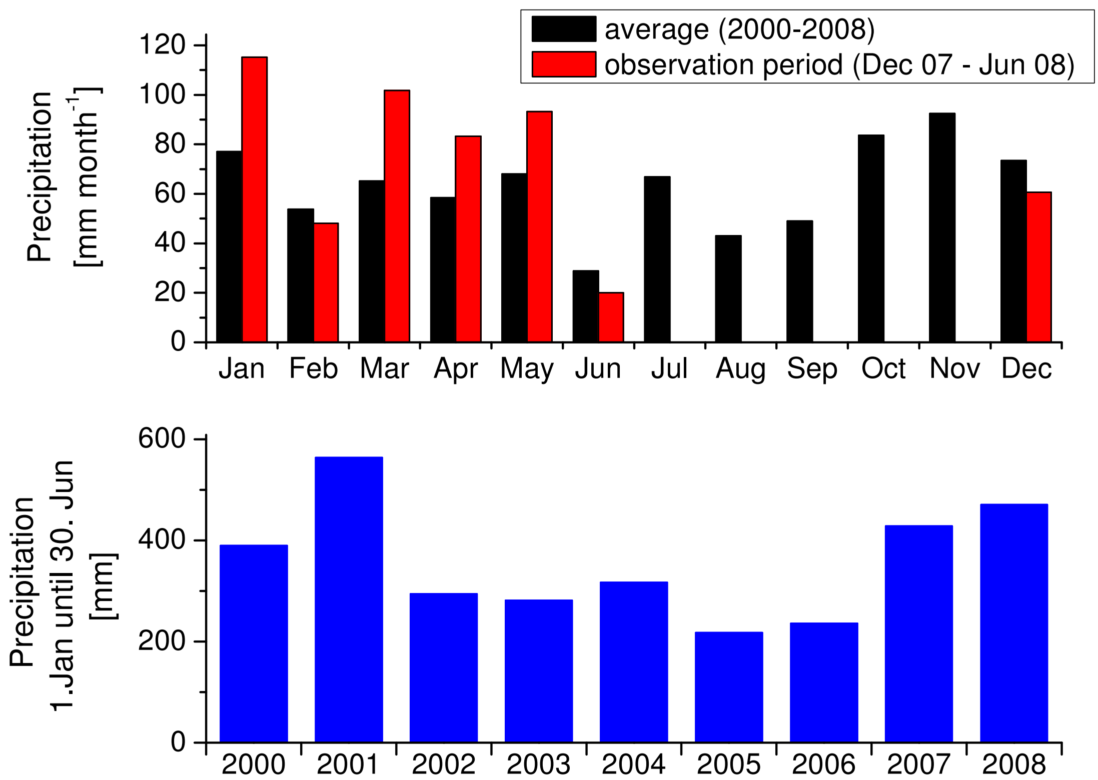

Figure 15: Comparison of precipitation during observation period with average values. Upper panel: average monthly precipitation (2000-2008) vs observation period; lower panel: average annual precipitation for the period January 1st until June 30th

3.3 Nutrient regime

3.3.1 Changes in chemical parameters along flows paths

Standard parameter analysis

Figures 16 and 17 present the conductivity and dissolved oxygen measurements using box plots (see section 3.1.2 for box plot method). Temperature, pH and redox data are given in the appendix 1. For each parameter, results from surface water are shown in the left graph, while the right graph shows piezometer measurements.

Figure 16 indicates that conductivity values are generally higher in piezometers than in surface water. Nevertheless in the piezometers A and C (see map Figure 7), the measurements are in the same order of magnitude as surface water. They may thus be influenced by infiltration of surface water. This seems likely as both piezometers are in close vicinity of surface water (PC is between basin 1 and ditch 1, PA is between the two basins). Moreover they are in the estimated flow path from basin 1 (see section 3.2.1).

In the basins, the entry and the ditch, water is in direct contact with the atmosphere, and as a consequence contains high oxygen concentrations, close to saturation. On the other hand, water of piezometers is characterized by low oxygen concentrations or anoxic conditions (Figure 17). The low oxygen concentrations indicate microbial degradation of organic matter and/or respiration of organisms.

pH values do not show great variations among sites (see plots in Appendix 1). However, slightly lower values are observed in the piezometers compared to surface water. The difference can be explained with processes of degradation of organic matter (pH decrease through NH_4 production) or respiration of organisms in the soil (pH decrease through CO_2 emanation).

Redox values are around 300 mV both in surface and sub-surface water, independent of oxygen level in the samples (see Appendix 1). As a result we conclude that the redox sensor did not work properly and will not use the data in the discussion.

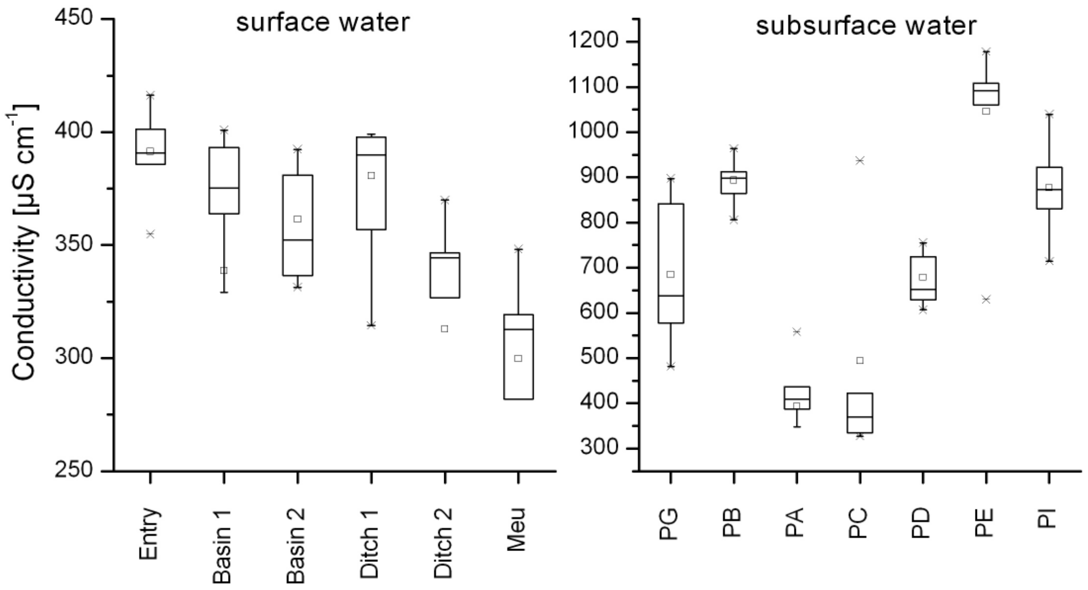

Figure 16: Box plot for conductivity [µS/cm], in surface water (graph on the left) and for piezometers (graph on the right), y-scale is different in the two plots.

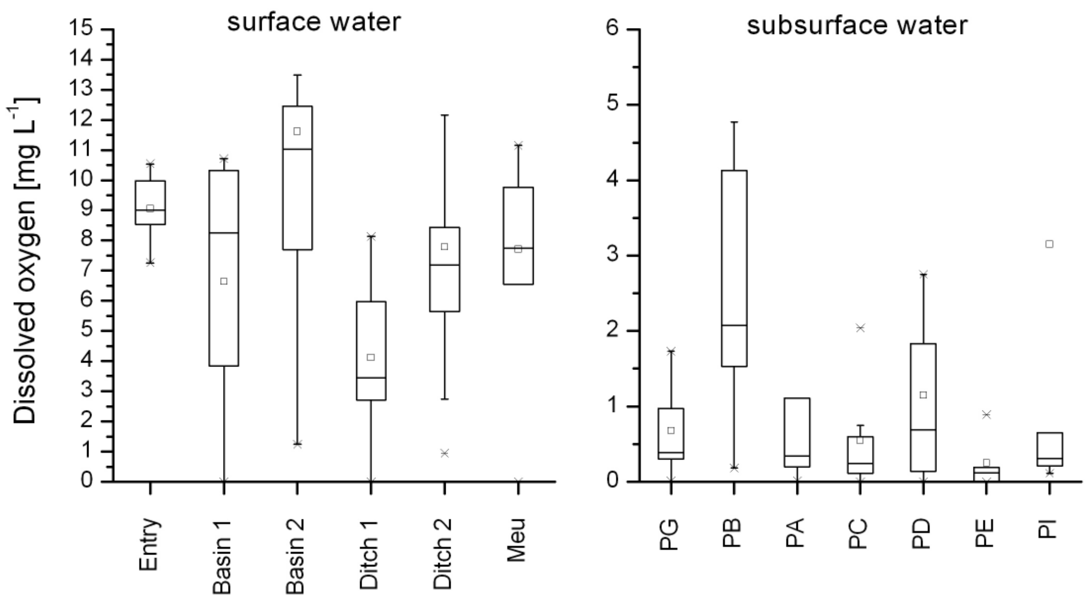

Figure 17: Box plot for oxygen [mg/L] in surface water (graph on the left) and for piezometers (graph on the right), y-scale is different in the two plots

Nitrate and ammonium analysis

Figures 18 and 19 present the nitrate and ammonium concentrations in piezometers and surface water. Box plots in the left part of the figures permit a general view of the order of magnitude of these chemical compounds. The curves on the right-hand side represent the temporal evolution of nitrates and ammonium between January and late May 2008

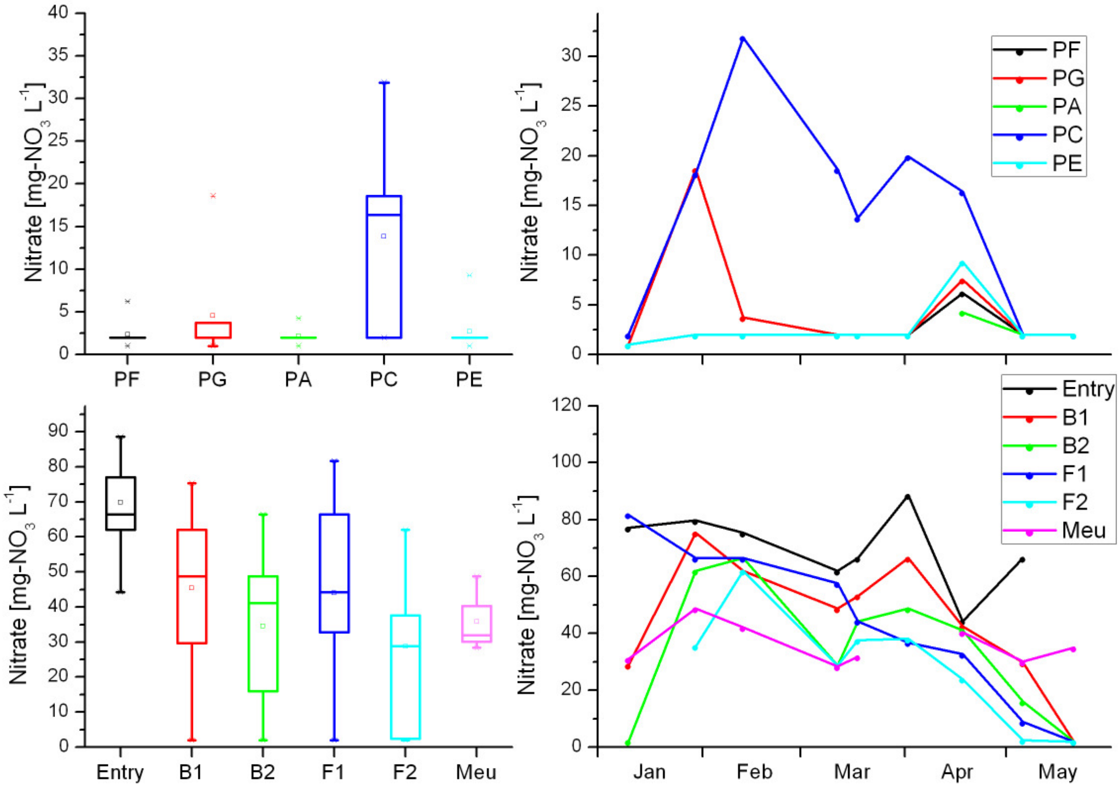

Figure 18: Box plots and temporal evolution of nitrate [mg-NO_3/L]. The top panels show piezometer samples, the lower panels surface water samples.

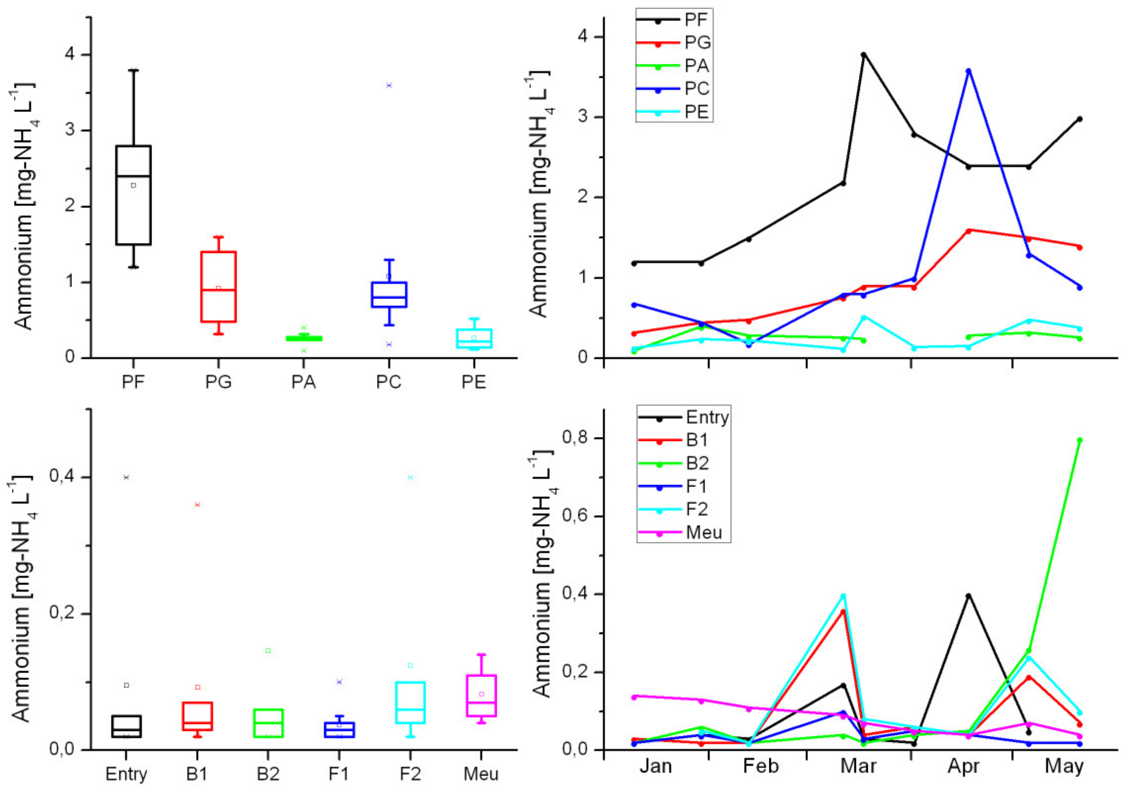

Figure 19: Box plots and temporal evolution for ammonium [mg-NH_4/L]

These box plots reveal important differences in nitrate and ammonium concentrations in piezometers and surface water:

For nitrates, the average concentration in piezometers is between 2 and 18 mg-NO_3 L^{-1}, whereas in surface water the averages are between 22 and 75 mg-NO_3 L^{-1}. Thus nitrates are significantly higher in surface water. The occasional higher values measured in PC could be explained by infiltration from surface water, as PC is between Basin 1 and ditch 1. This surface water influence is confirmed by conductivity measurements (see above).

For ammonium, the general trend is opposite to nitrates: averages of ammonium concentration are higher in piezometers (average between 0.2 and 2,5 mg-NH_4 L^{-1}) than in surface water (average below 0,1 mg-NH_4 L^{-1}).

Surface water contains high nitrate concentrations which stem pre-dominantly from agricultural applications and enter the wetland via drainage water. The low nitrate concentrations in the piezometers can be explained by (i) plant uptake during percolation and more importantly by (ii) denitrification. During denitrification nitrates are used as electron acceptor by microorganisms for the degradation of organic matter in the absence of oxygen. During the process, nitrates are reduced to gaseous N_2 or N_2O via a series of intermediate products:

$$\mathbf{NO_3^-} \rightarrow \mathbf{NO_2^-} \rightarrow \mathbf{NO} \rightarrow \mathbf{N_2O} \text{ gas} \rightarrow \mathbf{N_2} \text{ gas}$$

In turn, NH_4 is produced during the degradation of organic matter (from the nitrogen contained in organic matter). In the absence of oxygen, NH_4 is not oxidized rapidly and remains dissolved in the water.

Figure 20 and 22 represent measured nitrates concentrations along expected surface and subsurface flow paths (see section 3.2.1). Both new measurements and results from earlier campaigns (2005-2006) are shown.

The dominant share of the water, which passes the wetland via the two basins is clearly reduced in nitrate concentration for both monitoring periods (Figure 20). The more efficient reduction in past measurements is probably the result of the inclusion of periods without drainage inflow, where concentrations in the basins are diluted by direct rain water. This hypothesis cannot be tested, as inflow measurements are not available in the past. On the other hand, no nitrate reduction is found on February 13th 2008, during a high flow event. Not surprisingly, the data indicate that retention is strongly dependent on residence time within the basins. Although an overall reduction is observed, the nitrate level in the inflow is not reduced below the level of the River Meu for the high flow situation in 2008.

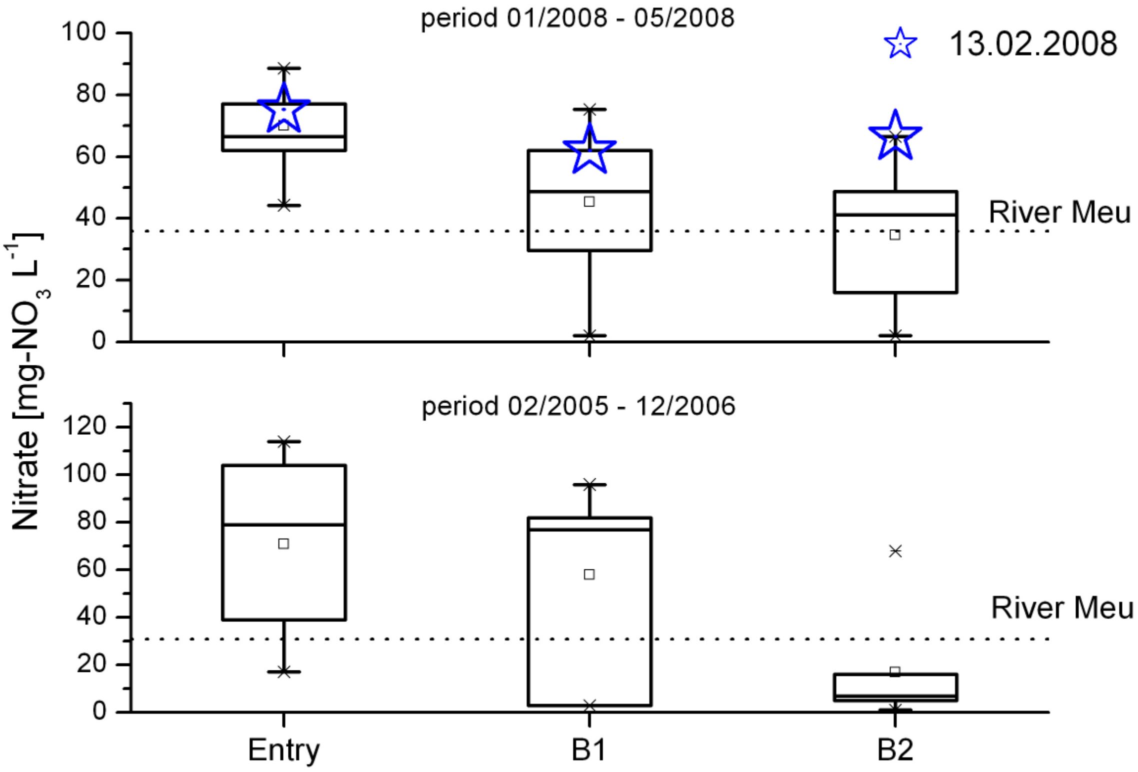

Figure 20: Evolution of nitrate concentrations [mg-NO_3 L^{-1}] along surface water pathway through the wetland for the current monitoring period 2008 (top panel) and for past monitoring 2005-2006 (SEEGT, 2006).

Figure 21 underlines the removal of nitrates along the sub surface pathway. Both for the current dataset and the 2005/06 dataset nitrate is removed by more than 90 % to below 6 mg-NO_3 L^{-1} in the piezometer, which is closest to the River Meu. The concurrent increase in NH_4 (Figure 21) indicates the expected anoxic degradation of organic matter, making denitrification the most likely reason of nitrate removal. The hypothesis is further supported by decreasing oxygen concentrations along the way (see Figure 17).

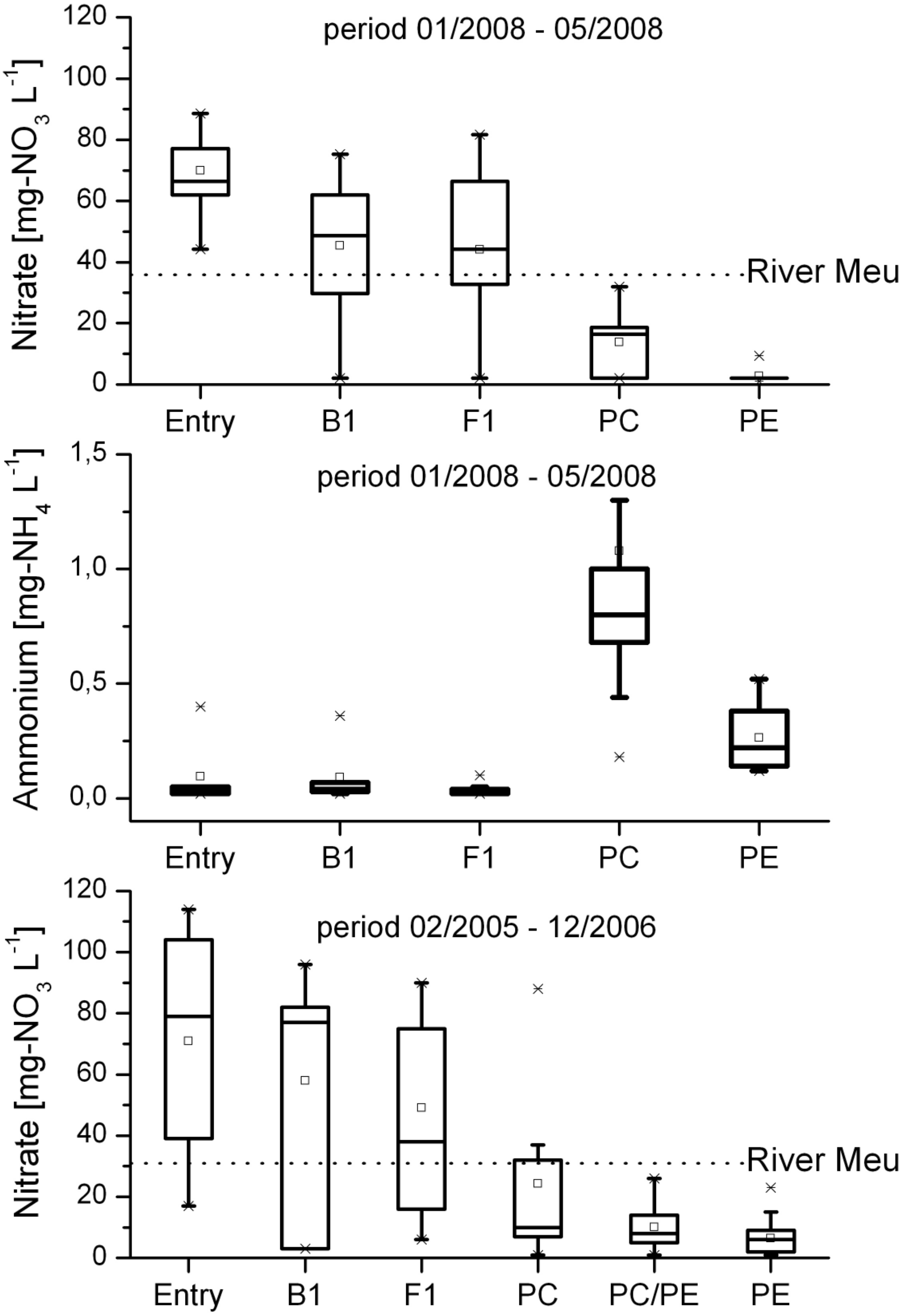

Figure 21: Evolution of the concentrations in nitrates [mg-NO_3 L^{-1}] for current and past monitoring activities. The dotted line indicates the average nitrate level of the River Meu for each time period. In addition to nitrate the evolution of ammonium [mg-NH_4/L] is shown for the 2008 dataset.

Orthophosphates and total phosphorus

Orthophosphate and total phosphorus concentration are presented for all surface water sites in Figure 22. The orthophosphate concentration is higher in all the surface water sites within the wetland than in the river Meu. Consequently, the wetland would be a source of orthophosphate for the river on the surface water pathway. Orthophosphate analysis in piezometers show very low concentrations, with very few measurements above the detection threshold of 0.1 mg-PO_4 L^{-1}. The low values are the result of the high adsorption of phosphorus to soil particles. Similar to nitrates, infiltration of drainage water would eliminate most of the phosphorus.

Total phosphorus was only measured in surface water. The total phosphorus in basin 2 is surprising. The high concentrations in the beginning of February and the end of May cannot be explained through drainage water inflow, as concentrations are lower in the entry (Figure 22). However the temporal evolution shows that high value in basin 2 is mainly the result of two measurements, which could potentially be the result from a re-suspension of sediments or be related to plant release following death and decay.

Overall there is no clear trend in P concentrations along the surface pathway through the system. This is surprising as P is expected to be sediment adsorbed to particles in the ponds. The residence time of water in the basins may be too short to get a decrease in phosphorus concentration. Furthermore, a remobilization of P is possible in restored wetlands if redox and hydrology change. In contrast, if the water follows a sub-surface pathway removal is almost complete.

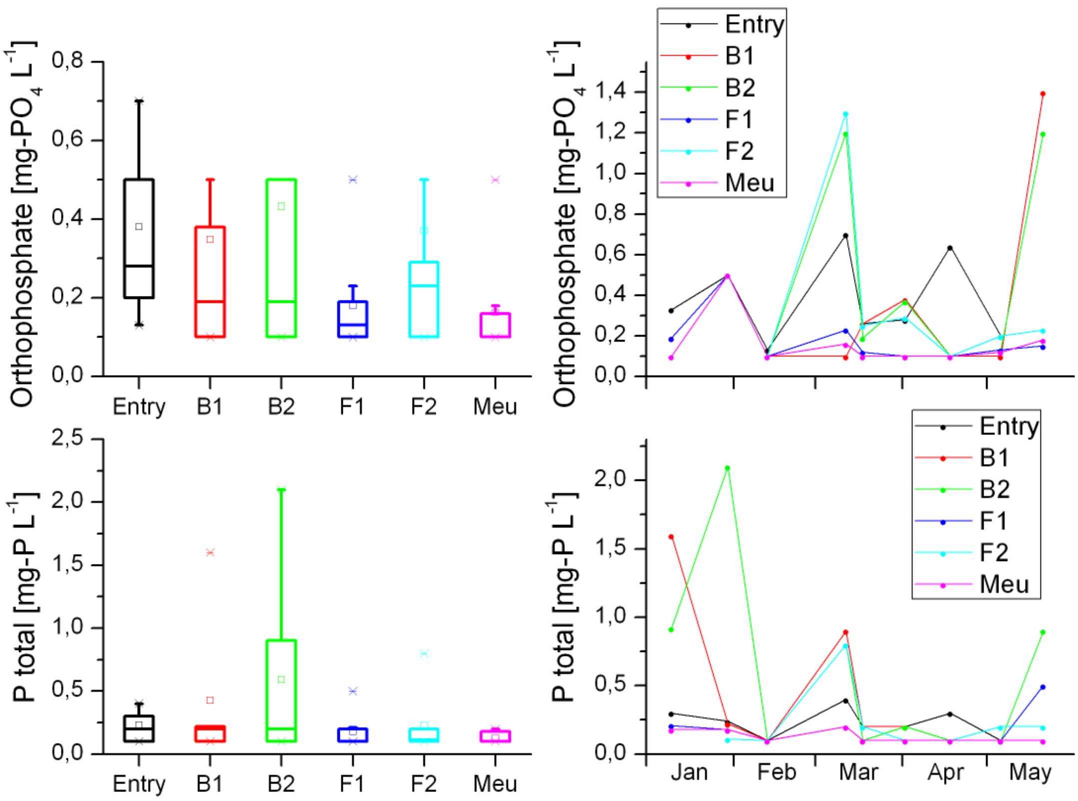

Figure 22: Box plots and temporal evolution for orthophosphates [mg-PO_4 L^{-1}] and phosphorus [mg-P L^{-1}] in surface water sampling sites

3.3.2 Nutrient mass balance

It is not possible to close the mass balance of the wetland, because of a lack in outflow measurements and continuous nutrient samples (nine samples from January to May). Moreover, continuous inflow is only available for 2008. Consequently, only a very broad estimate can be made for the current monitoring period from January to May 2008.

Nutrient input

Given the limited data the simplest approach was chosen, by matching each nutrient measurement (C) with the drainage inflow (Q) at the time of sampling. By multiplying the C with the Q values results in a set of nine instantaneous loads. The load of nutrients from drainage inflow shows a clear peak during high flow in mid March (black squares in Figure 23). However, it has to be kept in mind that only one high flow event was captured, as they usually have a short duration. Integrating over the nine points shown in Figure 23 therefore leads to high errors by neglecting the flow variability. On the one hand, several important inflow events are neglected. On the other hand, the measured points get a high weight, including the flow event in March.

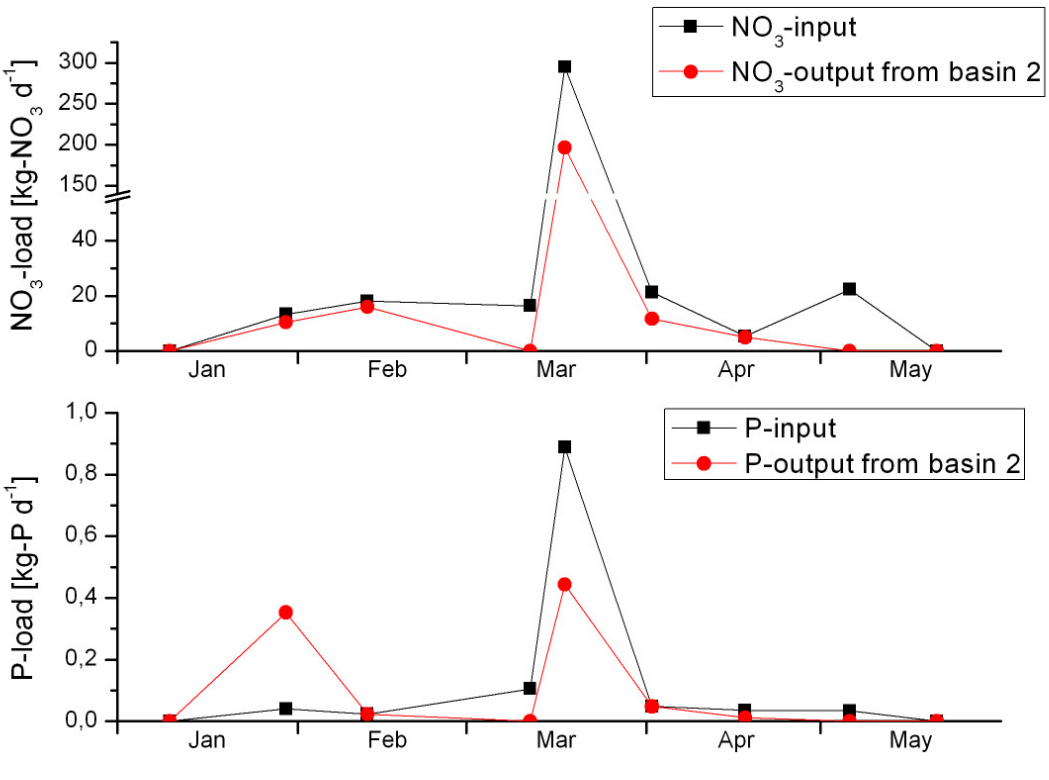

Figure 23: Estimated in- and outputs of nitrate and total phosphorus to/from the wetland via surface pathway through the basins.

Keeping these uncertainties in mind we integrated over the available points, interpolating linearly in between. The integration resulted in an overestimation of inflow (70 000 m^3 versus 53 000 m^3), and a input of 4800 kg-NO_3 and 14 kg-P over the entire period.

Retention in basins

Nutrient output via overflow to the Meu was estimated with the same method as for the inflow, by multiplying concentrations in basin 2 with the inflow from the drainage ditch (Red circles in Figure 23). During times when no overflow was expected (beginning of January, early March, in May; see Figure 14) flow was set to zero. The integration resulted in an estimated outflow of 60 000 m^3, which again is obviously too high. Nevertheless the share of water retained in the system of 14 % (in the simplified integration) is similar to the water balance in section 3.2.2 with 22 %.

Based on the simplified calculations average retentions of 40 % and 15 % are found for nitrates and total phosphorus, respectively. Although highest loads enter the Meu during high drainage inflow, retention in the wetland does not seem to be reduced during these events. This result should not be over interpreted, given (i) the sparse data and (ii) the lack of possible explanations for high retention during short residence times of less than a day. Nevertheless the results indicate that the wetland does reduce the nutrient load to the Meu even under suboptimal flow conditions.

Retention through infiltration

Both nitrates and phosphates can be assumed to be retained almost completely if the water infiltrates and follows a sub-surface pathway. However, only about 0,6 % of total nutrient input can be retained by sub-surface passage, giving the small infiltration (Table 1).

Overall mass balance

According to the above calculations up to 41 % of nitrates and 16 % of total phosphorus could be retained by the wetland (including ~0.6 % via infiltration). The remainder flows to the River Meu via overflow from basin 2.

3.4 Conclusions

The monitoring showed that inflows from drainage ditches in Brittany are likely one of the major sources of nutrients to the rivers of the region. As a result the constructed (though natural) wetland between a drainage ditch and the River Meu near Iffendic follows a very sensible approach.

The wetland was built as a series of ditches and basins to allow for a maximal infiltration. As planned, subsurface flow paths flow through the wetland towards the River Meu. However, the share of infiltration turned out to be less than 1 % of the total water volume, because of low soil permeability and high flow events after rain storms. As a result the major share of the drainage inflow flows through the two basins before directly overflowing to the River Meu. Finally about 20 % of the water is retained in the system.

Despite the suboptimal wetland hydrology, up to 40 % of nitrates and 15 % of phosphorus are retained in the wetland. These numbers could probably be further improved by (i) enlarging the basins, (ii) increasing the residence time in the drainage ditch (e.g., by installing small cascades) or (iii) by filling the drainage ditch with organic substrate, such as straw or bark mulch.

4 Floristic inventory

Restored wetlands are expected to allow an increase in plant diversity and to serve as important islands for animal migration. In order to evaluate the value of a constructed wetland, optimized for flood protection and contaminant retention, plant re-colonization was assessed for the wetland in Iffendic. The floristic inventory was realized on September 3rd 2008 along two transects of one hundred meters each, across the two basins.

4.1 Methods

Transects were chosen to be perpendicular to each other. Plants were identified along the transects in samples of one square meter each in 10, 15 or 20 meter intervals (Figure 24). In each sample all the plant species and the percentage of ground covered was recorded. In addition plants around the basins were identified to get a more complete assessment of biodiversity.

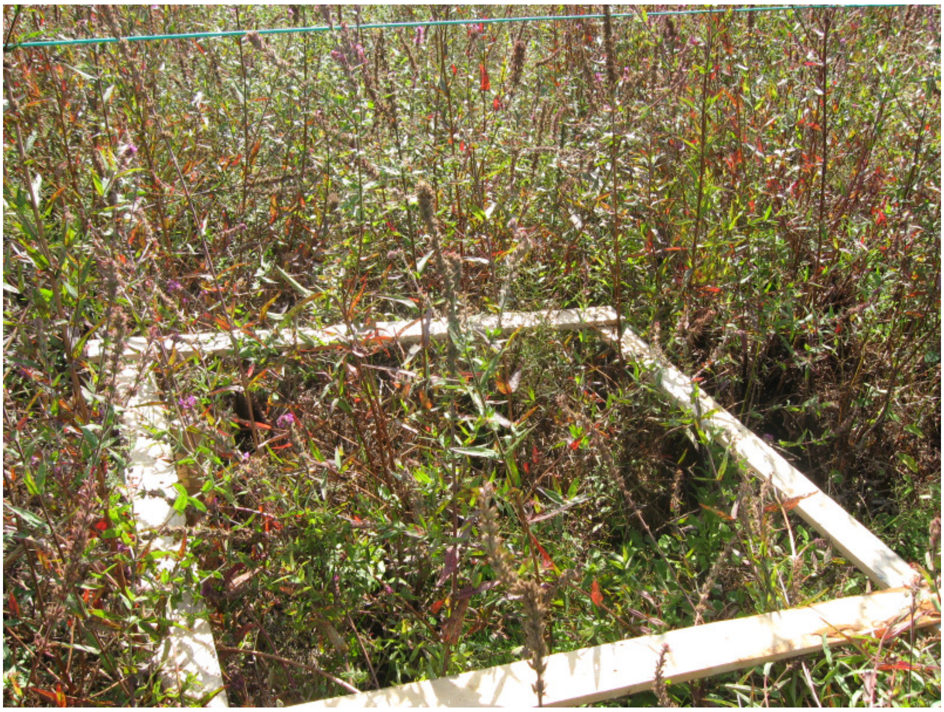

Figure 24: 1 m^2-sampling frame on basin 2 transect

4.2 Results

15 species were found in basin 1, based on 5 m^2 sampled and 21 species for larger basin 2, based on 8 m^2 sampled (Figure 25). However, plant observations outside of the sampled squares resulted in seven additional species in the first basin, indicating that the

sampled surface was not representative. With the additional species both basins show a similar number of plant species (Figure 25).

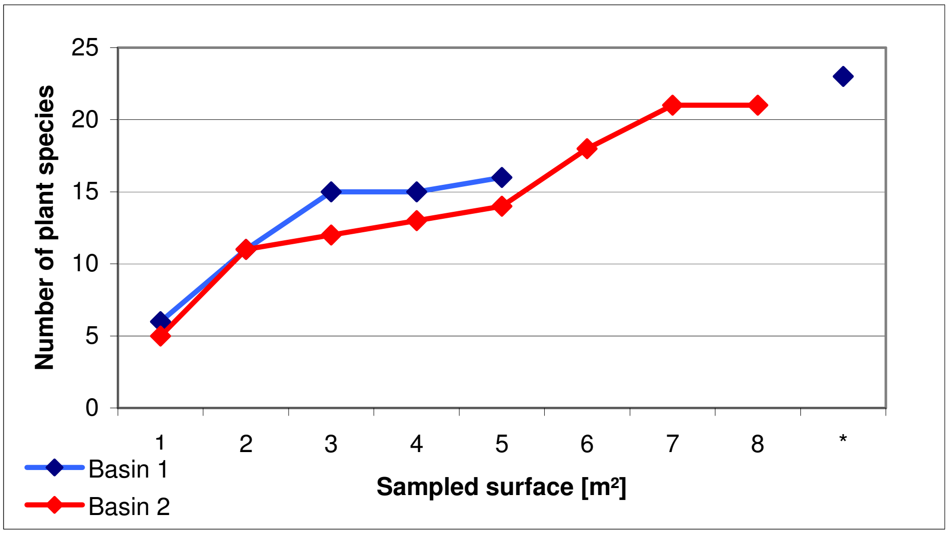

Figure 25: Number of species in each basin according to sample surface. The right-most point for basin 1 (indicated with a * on the x-axis) was completed with additional samples.

Dominant plant communities were mapped for the wetland by including samples outside the basins (Figures 26 and 27). Both basins show heterogeneous vegetation with several distinct plant communities. Nevertheless, the vegetation pattern is more homogeneous in the second basin.

The following communities were observed:

-First basin (numbers correspond to areas in Figure 26):

1. Community of, *Sparganium erectum* and other high herbaceous plant
2. Community of *Lythrum salicaria* and small hydrophyte
3. Community of *Typha arundinacea*
4. Community of graminacea (*Glyceria fluitans*) and little hydrophytes like *Alisma plantago*
5. Community of *Lythrum salicaria* but with an important development of *Calystegia sepium*

-Second basin (numbers correspond to areas in Figure 27):

6. An important high density community of *Lythrum salicaria*
7. An other community with *Lythrum salicaria* but in low density
8. Community of graminacea (*Glyceria fluitans*) and little hydrophyte like *Alisma plantago*
9. Herbaceous community of Carex sp or *Hydrocotile vulgaris*

Samples taken on the pool bank and around the basins showed an important development of *Calystegia sepium* in the North of the wetland. Meadows were dominated by gramineous plants and ruderal species like *Cirsium arvense* or *Agrostis stolonifera*. These ruderal plants dominated the southern meadow and pool bank, but presence of hydrophytes was significant.

The dominance of ruderal plants can be explained with a lack of moisture in the end of summer. Earlier, less systematic observations showed a dominance of wetland plants. This is also indicated by numerous dry hydrophytes in the second basin. However, ruderal plants were not recorded in the second basin, since their niche was occupied by high density of *Salix atrocinerea.*

Although most meadows are dominated by gramineae, the area between basin 2 and the River Meu is dominated by *Juncus effusus* and *J.conglomeratus*. Between basin 1 and the River Meu *Phalaris arundinacea* and *Typha latifolia* were recorded.

A complete list of recorded plant species is shown in Appendix 2.

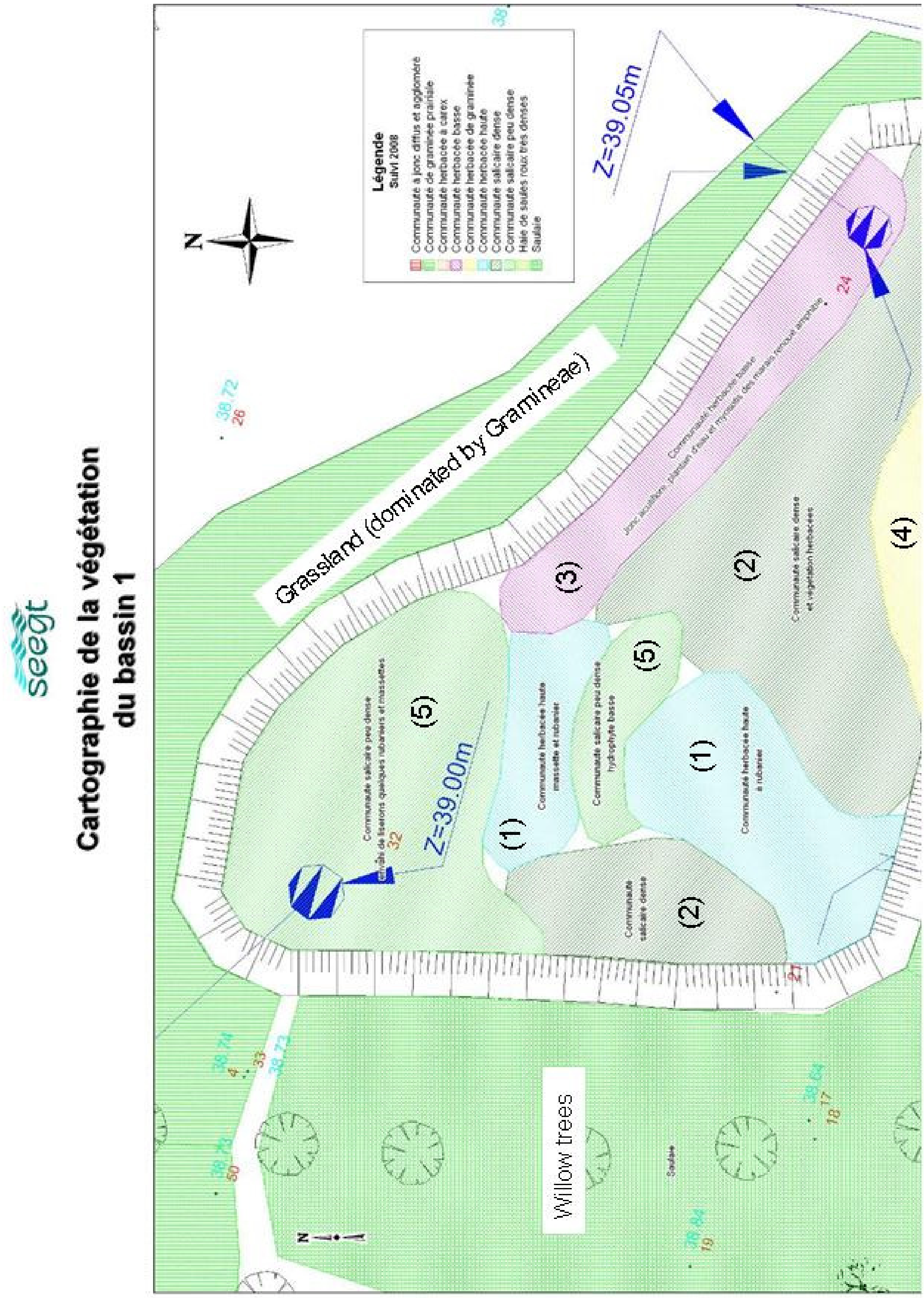

Figure 26: Plant mapping for basin 1. Numbers in parentheses match colors to community numbers described in the text.

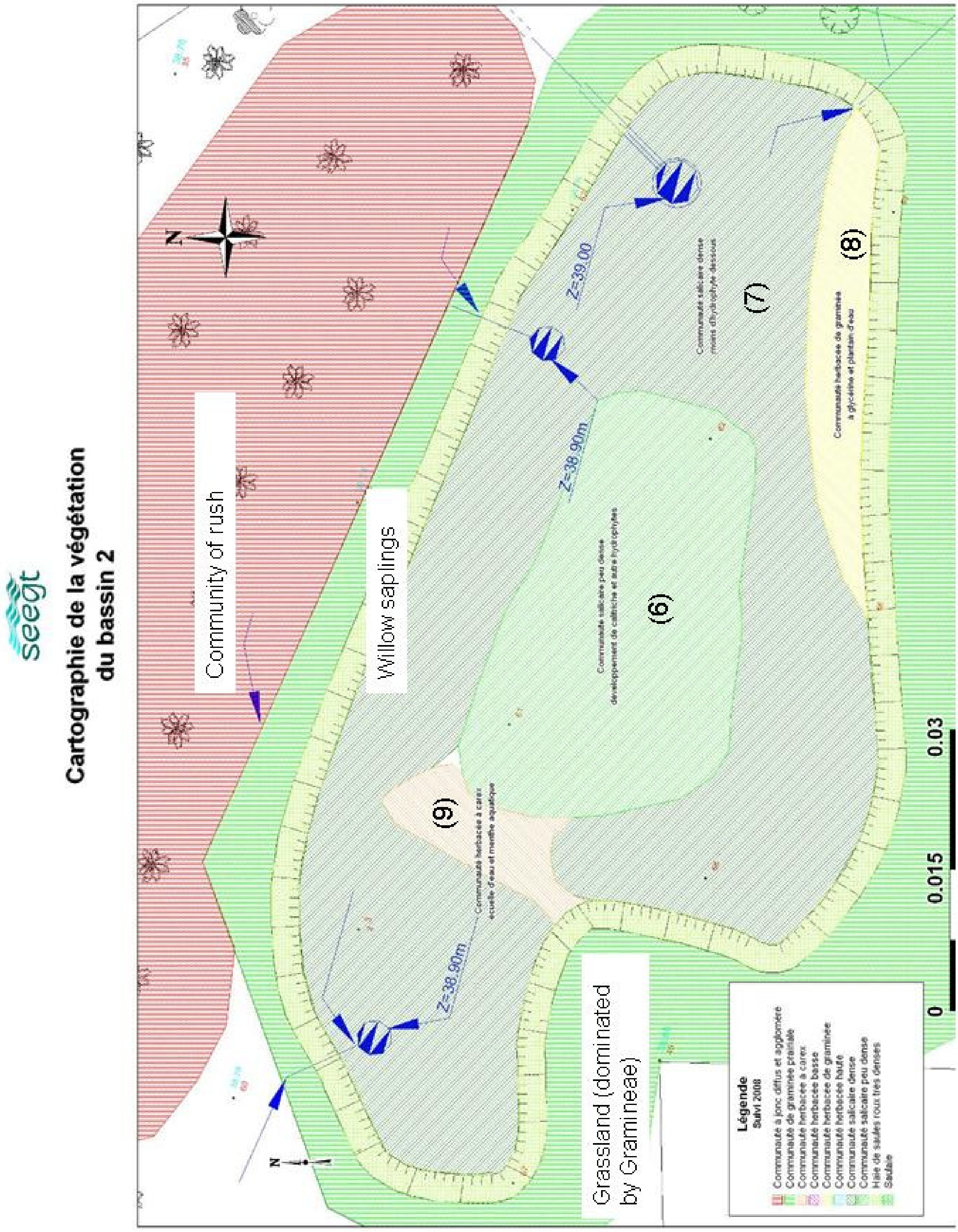

Figure 27: Plant mapping for basin 2. Numbers in parentheses match colors to community numbers described in the text.

4.3 Conclusions

In total 64 plant species were recorded in the wetland. Overall species diversity was similar in all habitat types (Figure 28). Grassland species were similar to the ones expected on prairies used by farmers. Major oligotrophication, which would lead to more diverse communities, has not been observed in the wetland, most probably because of the high nutrient loading from the drainage inflow. Nevertheless the habitat diversity, provided by the wetland restoration allows ~5 times more species than a farmed field (Figure 28). The overall diversity might be increased by further small-scale variation of the topography.

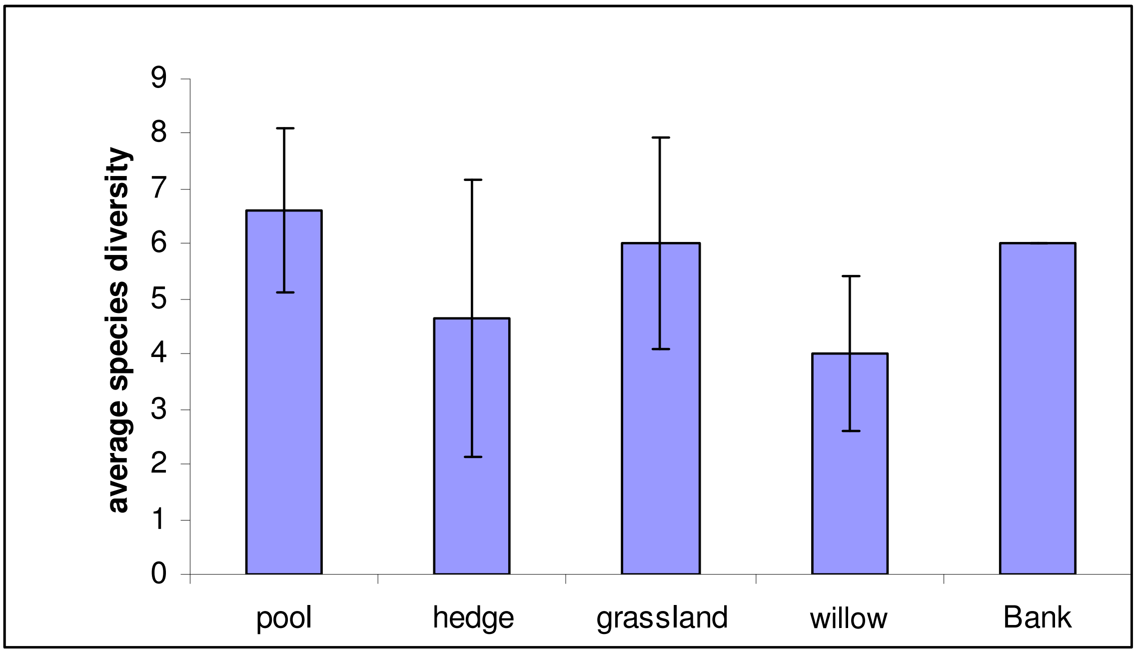

Figure 28: Number of plant species for each major habitat

In terms of species, no red-list plants were observed in the wetland. However, since some species can only be identified in certain vegetative periods, this may not be final. For instance there are rare species of the *Carex* genus, which was frequently observed in the wetland, but could not be identified to the species level.

Thus, to get a complete picture, plant inventories in different seasons would be necessary. Instead of looking manually for other plants, quadrats could have been randomly placed around the center point of the wetland. A method like this would be more inclusive of rare species. Keeping these methodological limitations in mind, one can conclude that restored wetlands make a significant increase in biodiversity, even if used to mitigate diffuse pollution.

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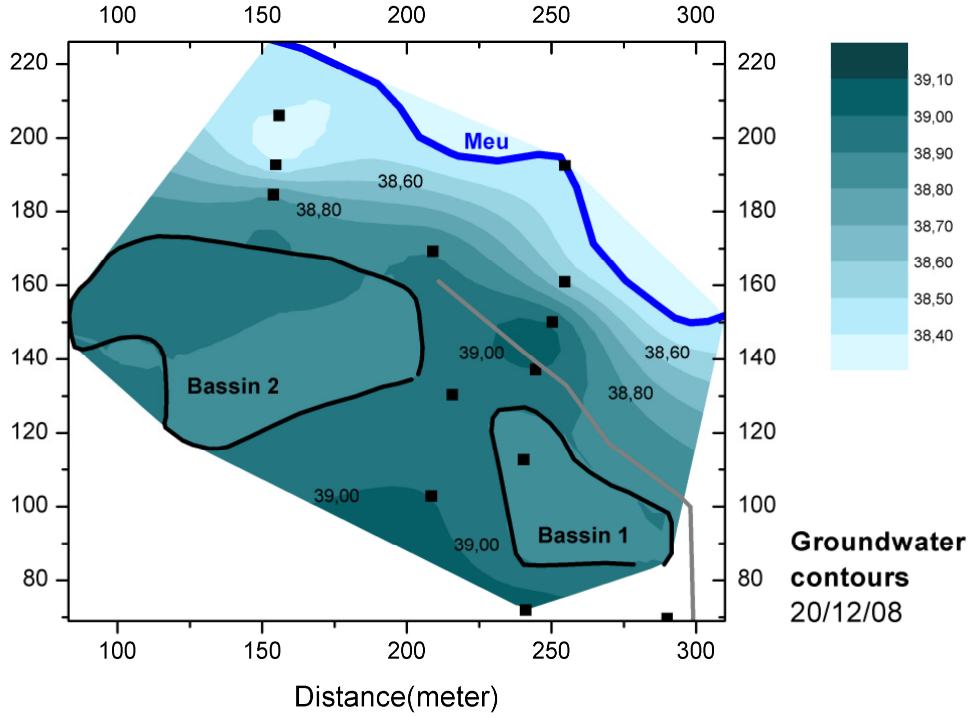
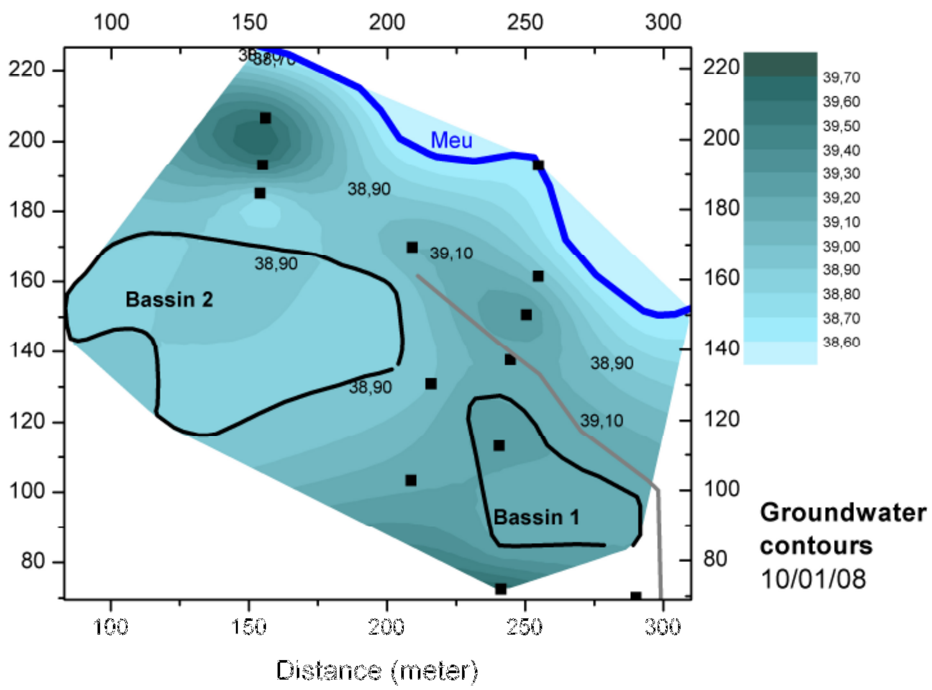
SEEGT. 2005b. Suivi de la zone humide en amont du Moulin de Delieuc à Iffendic. Bilan et perpectives. Syndicat Intercommunal du Bassin Versant du Meu. 10pp.

Further information was taken from: www.bretagne-environnement.org and www.infoterre.com

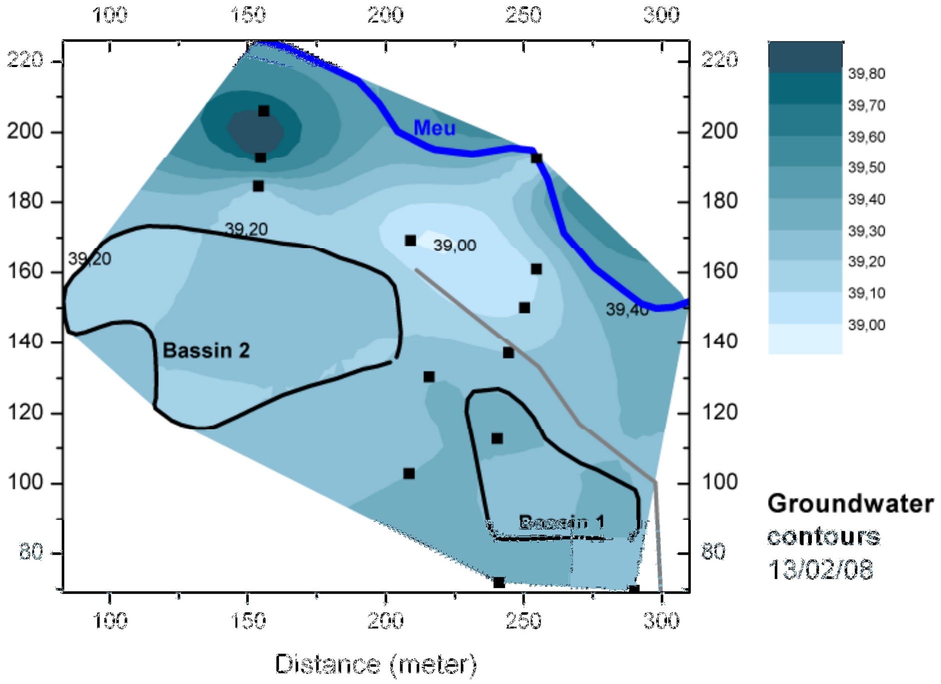
Appendix 1: Groundwater contours



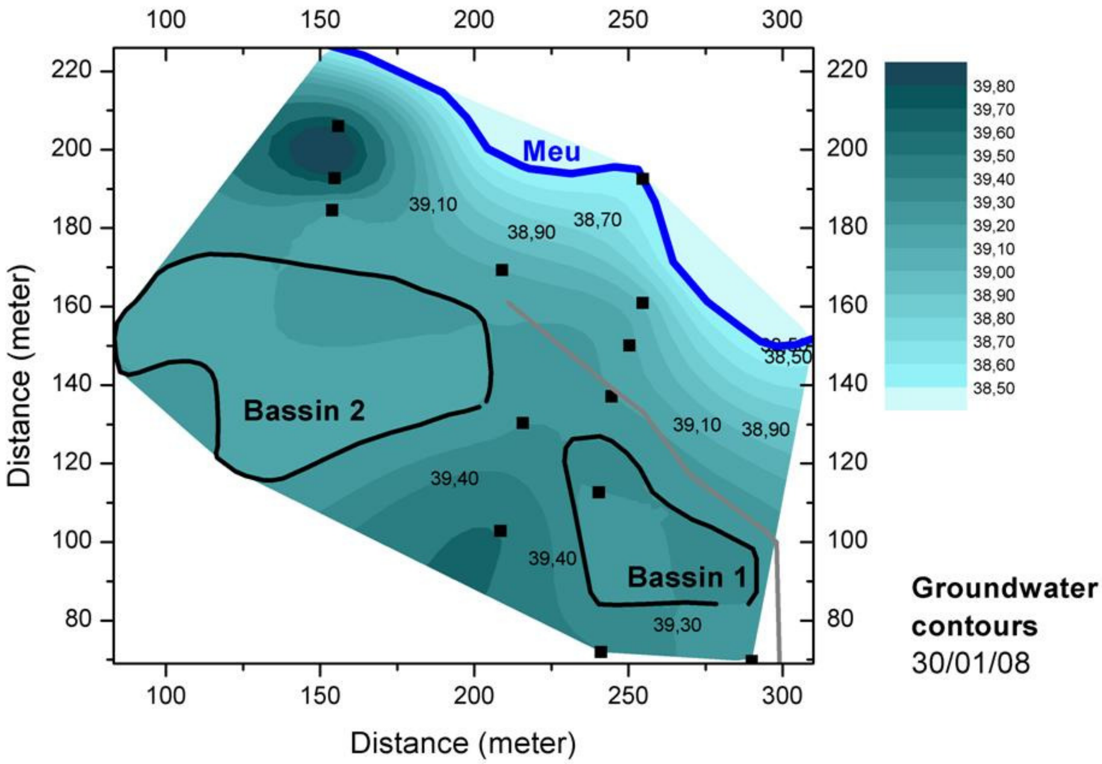
Water table elevation in meters above sea level for the 20/12/2008



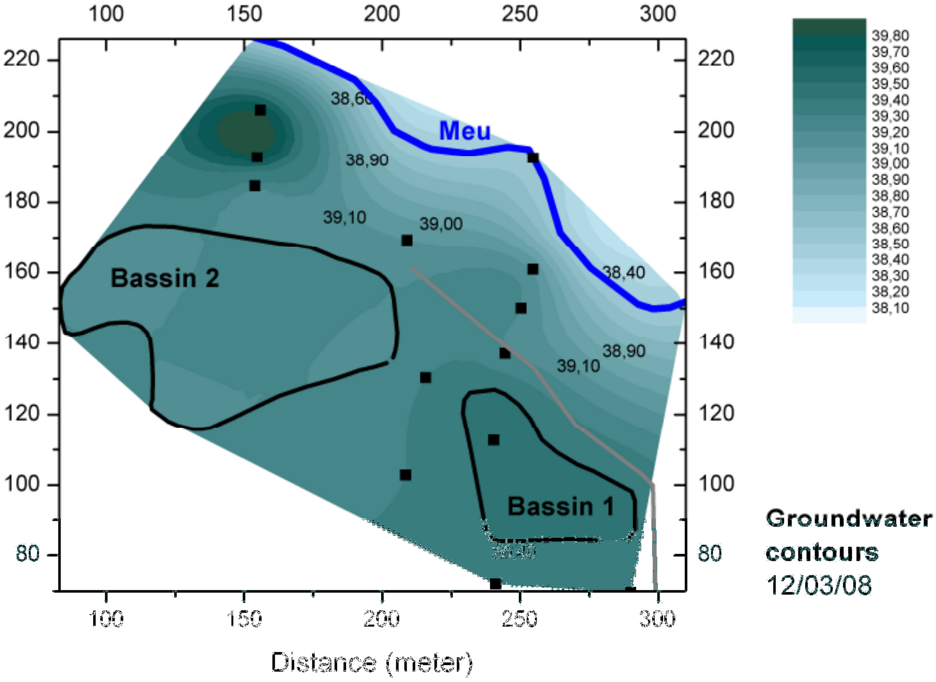
Water table elevation in meters above sea level for the 10/01/08



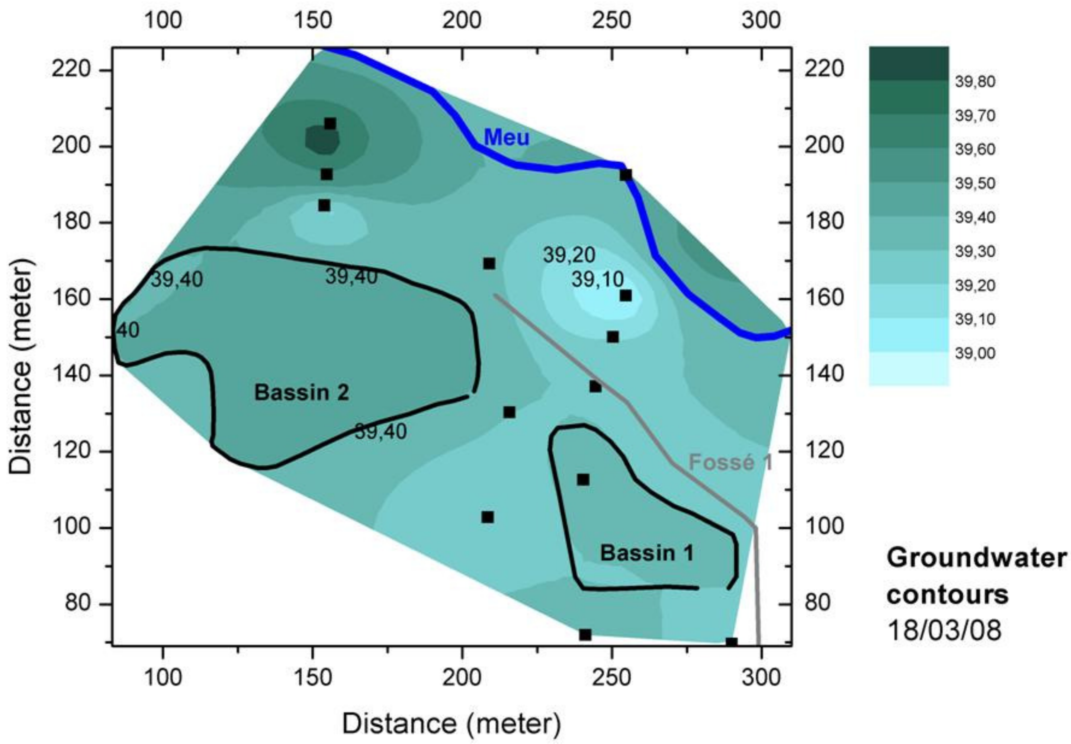
Water table elevation in meters above sea level for the 13/01/08



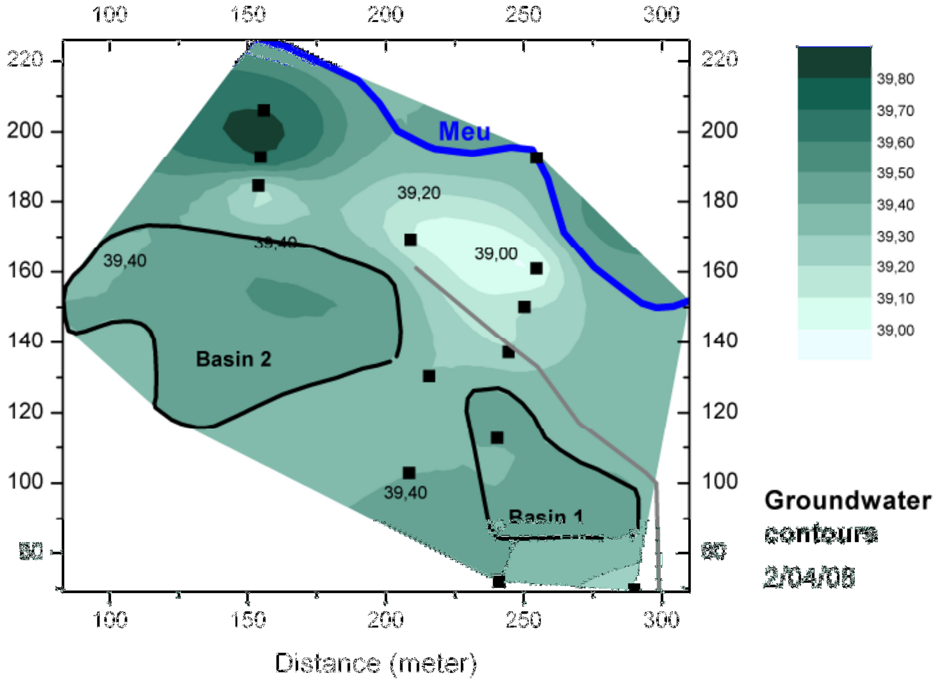
Water table elevation in meters above sea level for the 30/01/08



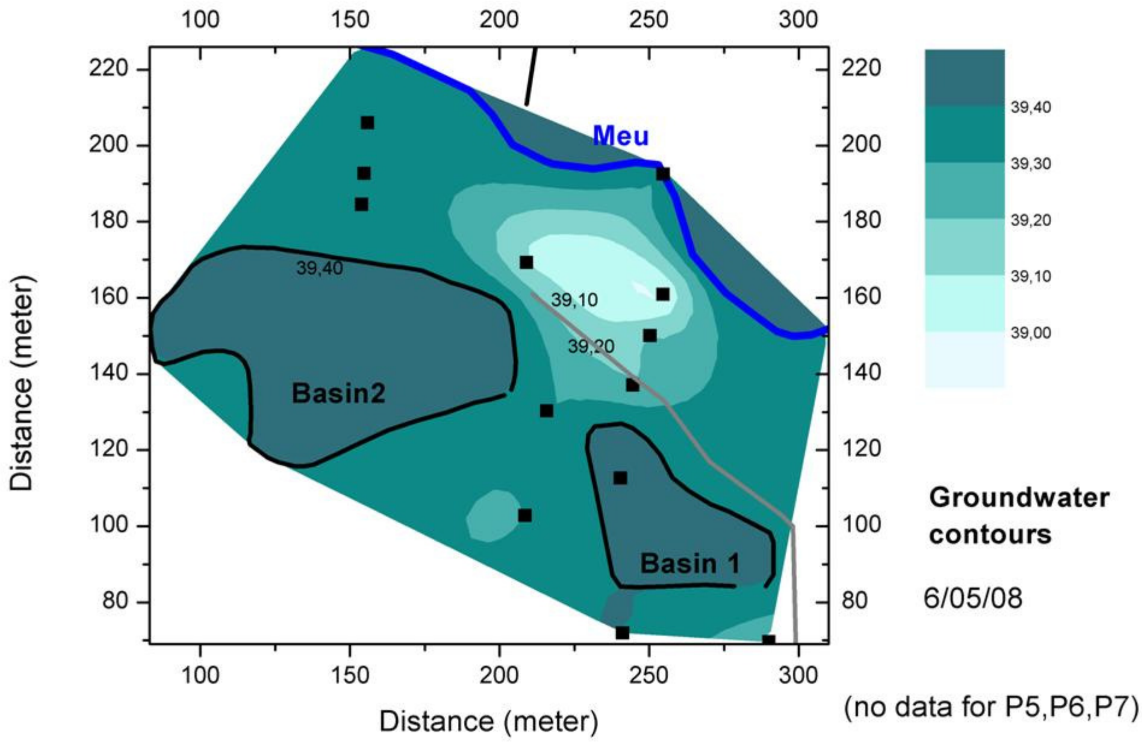
Water table elevation in meters above sea level for the 12/03/08



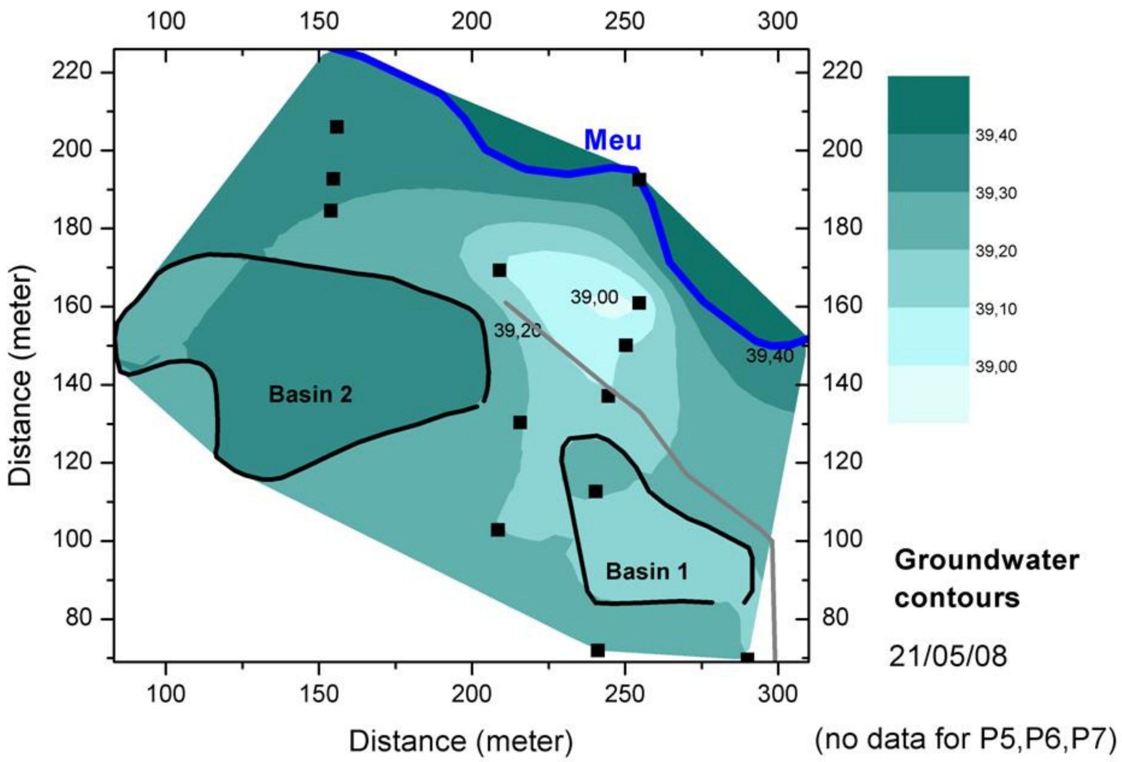
Water table elevation in meters above sea level for the18/03/08



Water table elevation in meters above sea level for the 2/04/08



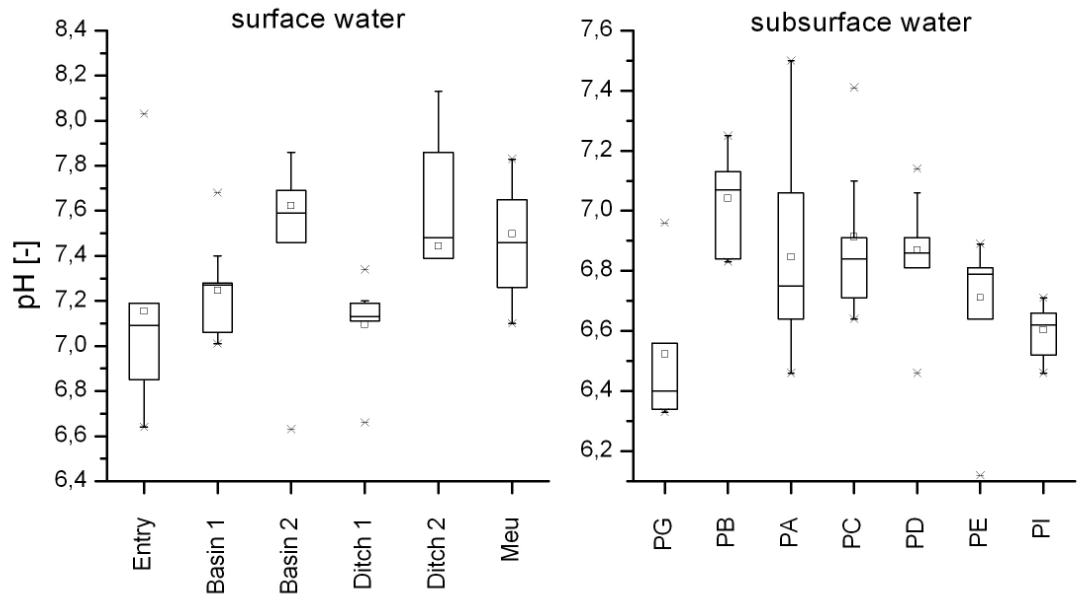
Water table elevation in meters above sea level for the 6/05/08



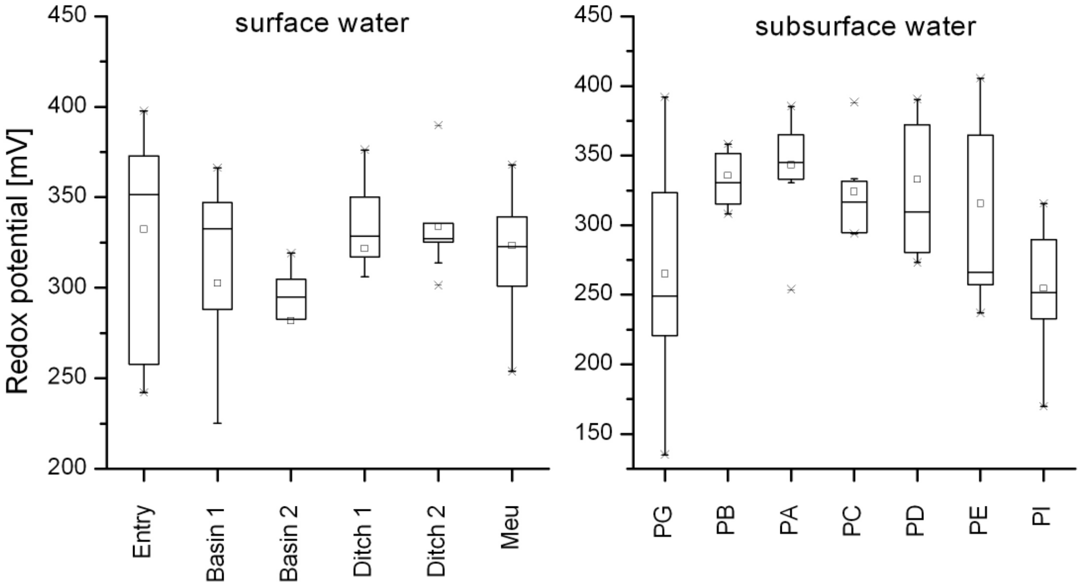
Water table elevation in meters above sea level for the 21/05/08

Appendix 2: Chemical standard parameters

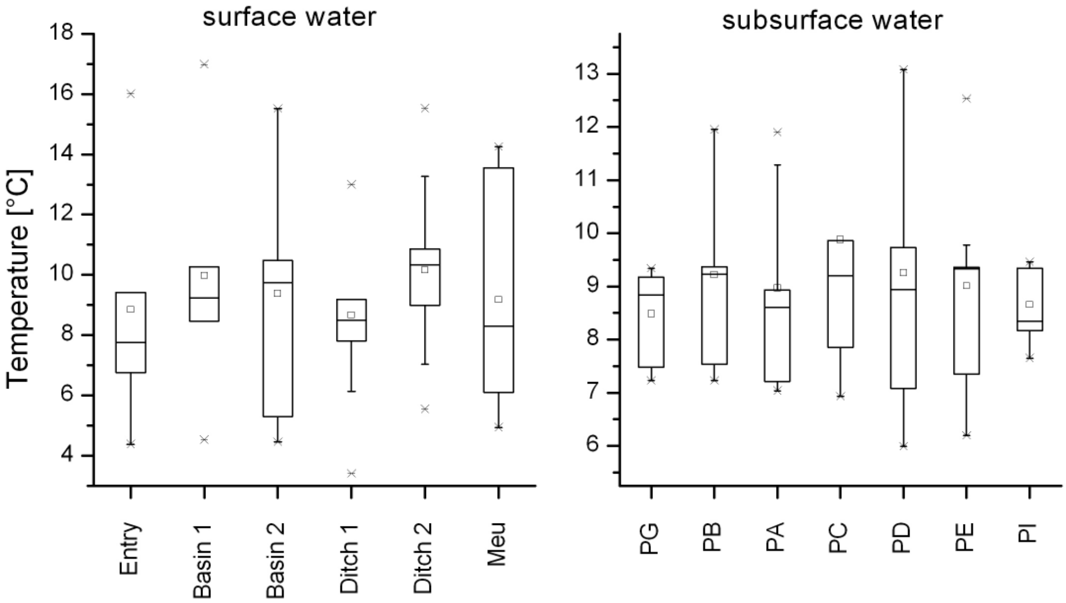
The plots below show standard parameters, which are not presented in main document (measured between December 2007 and June 2008).



Box plot for pH [-] in surface water (graph on the left) and for piezometers (graph on the right), y-scale is different in the two plots



Box plot for redox potential [mV] in surface water (graph on the left) and for piezometers (graph on the right), y-scale is different in the two plots



Box plot for redox potential [mV] in surface water (graph on the left) and for piezometers (graph on the right), y-scale is different in the two plots

Appendix 3: Recorded plant species

Recorded plant species on 03.09.2008	
A - Lotus	**Ly - Z**
Achilea ptarmica	Lycopus europaeus
Agrostis stolonifera	Lysimaquia vulgaris
Alisma plantago	Lythrum salicaria
Anthemis arvensis	Mentha aquatica
Callitriche stagnalis	MOUSSE X
Calystegia sepium	Myosotis scorpioïdes
Carex sp	Nasurtium officinal
chenopodium sp1	Oenanthe crocata
chenopodium sp2	Phalaris arundinacea
Chenopodum album	Plantago major
Cirsium arvense	Poa Trivialis
Cornus sanguinea	Polygonum amphibium
Eléocharis palustris	Polygonum maculosa
Elymus repens g coupante	Populus hybride
Epilobium hirsutum	Populus nigra
Filipendula ulmaria	Prunus spinosa
Galium palustre	Pulicaria dysenterica aster j
Glycéria fluitans	Quercus robur
Gnaphalium uliginosum	Ranunculus flamula
Graminé poilue	Ranunculus repens
graminé x	Rubus fruticosus
Hydrocotile vulgaris	Rumex acetosa
Iris pseudacorus	Salix atrocinerea
Jeune graminé x	Salix aurita
Juncus acutiflorus	Scirpus fluitans
Juncus bulbosus	Scirpus lacustris
Juncus conglomeratus	Solanum dulcamara
Juncus effusus	sp 1
Lamier rouge	Sparganium erectum
Lemna sp	Sphagnum sp
Lolium perenne	Stelaria media
Lotus corniulatus	Typha latifolia