Modelling surface water, groundwater and nitrate processes in a restored riparian wetland

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ABSTRACT: The restoration of rivers and riparian wetlands continues to be an important measure for reducing nutrient loads in Danish river basin plans required under the European Water Framework Directive. The environmental benefits of wetlands include improving biodiversity, water purification, flood protection, shoreline stabilization, groundwater recharge, and streamflow maintenance The effectiveness of riparian wetlands in providing both improved ecological conditions while reducing nutrient loads depends not only the water quality processes but also on the hydrological processes. As wetlands act as buffer zones for the river system intercepting both surface and subsurface flows, their functioning depends on the interaction between surface water and groundwater particularly during flooding of the wetland. To improve our understanding of the influence of these different processes on the functioning of riparian wetlands we have developed a detailed eco-hydrological model that represents the flow, transport and water quality processes in such a system. This model is used to examine both the surface and subsurface flow processes and the nitrate dynamics within a restored riparian wetland on the Odense River in Denmark. We assess the ability of this model to capture the surface and subsurface processes using measurements of flows and water levels in the river and wetland system including groundwater levels in profiles during both dry and wet periods. Simulation of the different nitrate processes in the river, wetland, soil and groundwater, is used to investigate nitrate reduction within this integrated system and the results are compared to in-situ measurements of nitrate concentrations in the subsurface.

INTRODUCTION

Riparian wetlands provide beneficial functions to the wider environment through their hydraulic connection to rivers and streams. Riparian zones intercept surface as well as sub-surface flow and thereby function as buffers for river systems, significantly reducing nutrient loadings through processes such as sedimentation and regeneration, de-nitrification/nitrification processes and to a smaller degree plant uptake, decay and mineralisation (Fisher and Acreman, 2004; Mayo and Bigambo, 2005). Riparian zones play a major role in water quality in watersheds, especially in low-order streams where the cumulative effects can have a large impact on downstream water quality (Rassam, et al., 2008).

Whilst most studies indicate improved water quality as a result of wetland restoration (Fisher and Acreman, 2004; Woltemade, 2000) the influence of extensive alterations on the hydraulic interaction between streams and their floodplains and the effect on nutrient processes have received limited attention (Walling and He, 1998). Detailed modelling studies of the role of wetlands in nitrate retention have been conducted but few include a linked physical representation of surface water flooding, unsaturated zone flow and subsurface flow combined with nutrient processes (Restrepo, et al., 1998; Langergraber and Šimůnek, 2005; Rassam, et al., 2008). This study has focused on developing a model capable of predicting the nitrate reduction capacity of re-constructed wetlands using a dynamic ecological modelling tool ECO Lab (DHI, 2009), coupled with a detailed dynamic physically based numerical flow and transport model MIKE SHE (DHI, 2012a; Graham and Butts, 2006).

This paper examines the nitrogen retention capacity of a restored riparian wetland located next to Odense stream using MIKE SHE ECO Lab (Butts et al., 2012; Loinaz et al, 2013, 2014). The model both investigates the potential for removal of nitrate coming from surrounding fields and for removal of nitrate transported by flood water into the floodplain. The study objectives were driven by the requirement to preserve and enhance the status of water bodies under the Water Framework Directive (2000/60/EC) and the work proposes an innovative and practical method to assessing the potential of wetlands in reducing nutrient loadings.

STUDY SITE: BRYNEMADE

The study site is a restored riparian floodplain of the River Odense on Funen in Denmark. The floodplain was restored in 2003 by re-meandering and reducing the flow capacity of the formerly straightened channel and encompasses a total of 125 ha riparian area, used as permanent grazing meadow following restoration. The re-meandered channel has a length of app. 6 km with 16 meanders (Figure 1). The channel bed level was on average raised by 1 m in the restored channel and the cross-sectional area was reduced by app. 50%. The site is characterised by frequent flooding post restoration (above a river stage of 24.42 m AOD), both during the winter and during summer storms. Further detail of the study area and the restoration can be found in (Poulsen, et al., 2014) and (Jensen et al., 2015).

The focus of this paper is a smaller wetland area covering 0.1 km^2 shown in grey (Figure 1) where a number of transects were established by (Poulsen, et al., 2014) in order to measure the hydraulics of the floodplain including water depths and velocities. A second set of transects were installed with the aim of recording groundwater levels and nutrient concentrations by (Jensen et al., 2015). The main purpose of the hydraulic measurements was to investigate the flow regime and sedimentation patterns of the floodplain (Poulsen et al., 2014) whereas the second set of transects was established in order to examine the ability of the wetland to retain nitrate. Both data sets were used for the development of the integrated flow and water quality model.

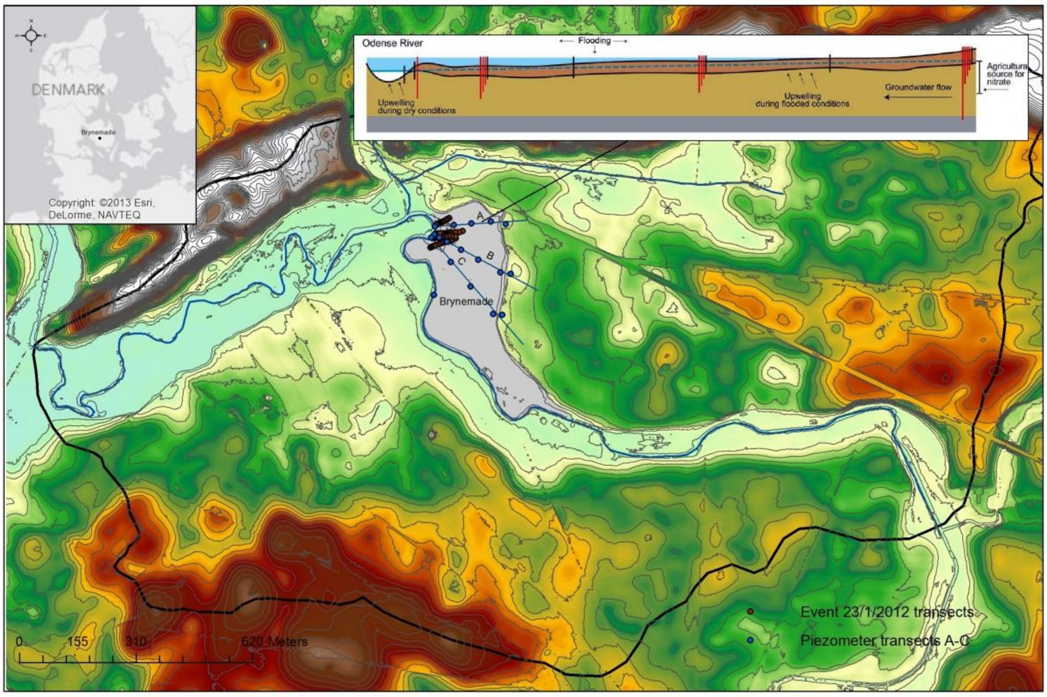

Figure 1: Overview of the model area. The wetland area of interest is highlighted in grey.

DATA

The catchment area upstream of the floodplain is 254 km^2 and is characterised by moraine deposits from the last glaciation period composed of a mixture of clayey and sandy soils. A simple geological model of the smaller transect area (Figure 1) was developed by the University of Copenhagen (KU) based on borehole data and geophysical measurements (Jensen et al., 2015). The geology here is relatively simple and consists of a thin layer of peat (app. 1 m) underlain by approximately 12 m of sand. Land use in the area is predominantly agriculture (65 %) while forests and smaller villages cover the remainder of the catchment. The catchment topography including the floodplain was extracted from the Danish Height Model (DHM) which is a digital elevation model maintained by the Danish Geodata Agency (GST). The DHM has a grid size of 1.6 m, a horizontal accuracy of 0.70 m and a vertical accuracy of 0.06 m. A number of river cross-sections along the restored section were surveyed in 2010, including a detailed cross-section at the wetland site.

Average annual rainfall (1989-2012) for the study area is 895 mm. Daily catchment rainfall data is available from the Danish Meteorological Institute (DMI) on a 10 by 10 km grid for the period 1989-2012 and potential evapotranspiration (PET) and temperature were provided on a 20 by 20 km grid (Danish Meteorological Institute (DMI), 2012). Minimum daily river flow at the site was 0.12 m^3/s, mean annual river flow 2.59 m^3/s and absolute maximum flow 16.6 m^3/s for the period 2003-2012. The Baseflow Index (BFI) for Odense Å is 0.67 (27 year period) which indicates that the catchment is groundwater dominated with some runoff. Stream flow measurements at the wetland were provided by Aarhus University for the period 2003-2012.

Groundwater level and water quality measurements were taken by Jensen et al., (2015). Groundwater levels in the sand aquifer have been measured in 17 piezometers located along the three transects shown in Figure 1. Levels were recorded under different conditions during 2011 on five dates: 17/1 (wet), 10/5 (normal), 2/7 (dry), 20/7 (wet) and 30/8 (normal). Water quality data consist of sample measurements of concentrations of nitrate (NO_3), ammonium (NH_4), oxygen (O_2) and other compounds (Cl, SO_4, NO_2, Fe, Mn) taken at the piezometer locations along transects A-C over 2-3 days at different depths during 2010-2011. Measurements are available on: 13/4-15/4 (2010), 4/10-6/10 (2010) and 4/5-5/5 (2011), Jensen et al., 2015.

METHODOLOGY

Flow and water quality modelling was carried out in two stages: first a dynamic 3D-hydrological model (MIKE SHE) was set up in order to describe the hydrology of the site; the flow outputs from this were subsequently used for running the water quality module of MIKE SHE (MIKE SHE-ECO Lab) for investigating the nitrate retention of the wetland. MIKE SHE is a physically grid-based integrated surface water-groundwater model. The model provides a physical representation of surface, near surface and sub-surface flow. It uses a finite difference formulation of a 2-D model for overland flow combined with a 1-D river model (MIKE 11), a 1-D model of unsaturated flow and a 3-D description of saturated flow (Graham and Butts, 2006).

The water quality module in MIKE SHE was used for describing the advection-dispersion transport (conservative) processes and ECO Lab, an ecological process model (DHI, 2009) handles the water quality simulations of the sink and sources in the advection-dispersion equations. ECO Lab is incorporated in the user interface of MIKE SHE and uses a process based description with standard templates as a basis. The modelling approach developed here takes account of the main nitrogen removal processes identified in riparian wetlands including nitrification, denitrification, plant production and nutrient uptake, plant death, mineralisation and adsorption. A schematic of the processes is shown in Figure 3. The processes are assumed temperature dependent and include surface water flooding processes, unsaturated zone processes and saturated zone processes. In the model nitrification and denitrification are described by temperature dependent Michalis-Menten or first-order equations (Dørge, 1991). The denitrification rate in saturated peat is assumed to be depth dependent using an exponential decay function presented by Rassam et al. (2008). Plant production and uptake in the wetland are calculated using a simple approach based on light radiation and does not currently depend on nitrate or ammonium concentrations.

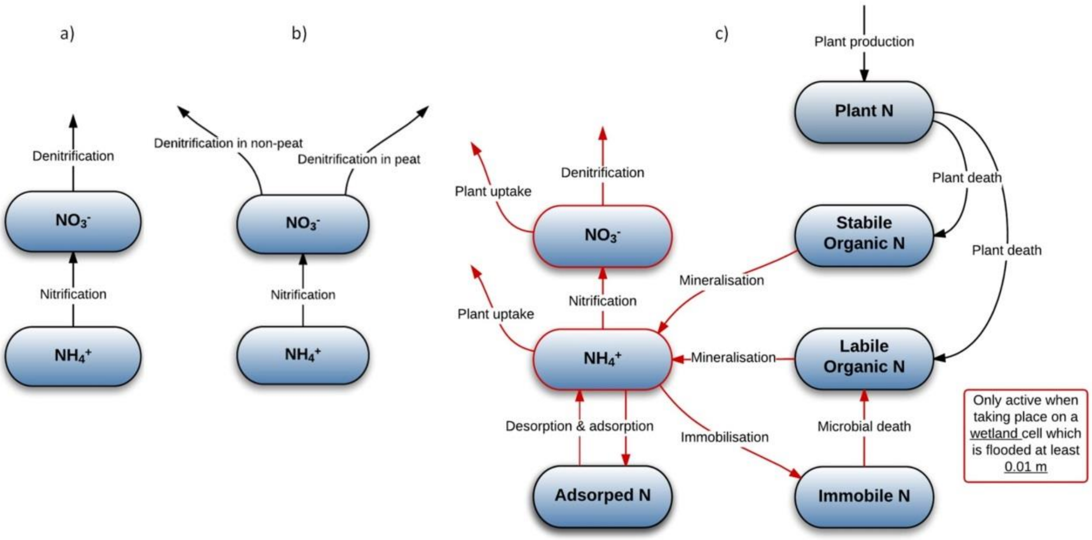

Figure 3: Nitrate processes included in the MIKE SHE-ECO Lab model for Brynemade: a) unsaturated zone processes, b) saturated zone processes and c) overland processes

FLOW MODEL SETUP

A conceptual and numerical hydrological dynamic model capable of capturing the floodplain flow dynamics, including exchanges between the river and floodplain, river and groundwater as well as floodplain and groundwater was developed based on the information above. The model covers the catchment area of the restored floodplain of 3.1 km^2 (Figure 1) and was delineated based on topographic divide, assuming that the groundwater divide of the underlying shallow sand aquifer and topographic divide coincide. This is typically a reasonable assumption for shallow permeable aquifers (Haitjema and Mitchell-Bruker, 2005).

A catchment model with a spatial resolution of 25 by 25 m^2 was set up, initially. Based on this model a smaller local flow model with the same resolution was also developed which covers the riparian wetland shown in grey in Figure 1. This model takes the time varying boundary conditions from the larger model and was developed to investigate the nitrate processes in the wetland. Computational layers were defined based on a simple geological transect model (Figure 1) with a shallow layer of peat of 1 m underlain by a 12 m thick sand aquifer. In reality the geology is more complicated than this but for the purposes of this study, which focuses on the floodplain this is considered a reasonable assumption. The model was set up using different vertical resolutions. A simple flow model with two computational layers in the saturated zone representing the peat and sand layers was initially set up in order to calibrate the flow model and develop an understanding of the importance of the peat layer with respect to flow and nitrate processes. The model was then refined with one layer representing peat and several layers (eight in total) representing the sand aquifer to be able to represent the movement and removal of nitrogen at different depths.

MIKE SHE requires a number of other input parameters which initially were set based on a combination of available field measurements, default parameters typically used for Danish catchments and modeller experience. The surface roughness (Manning's M) of 5 m$^{1/3}$/s was already calibrated by Poulsen et al. for a flood model of the area. Manning's M for the river model was initially also taken from Poulsen et al. but was subsequently calibrated based on daily recorded stages from 2011. Soil parameters for the upper layers in the unsaturated zone were estimated from general information on Danish soil types. Estimates of the hydraulic conductivity for peat and sand were obtained from field measurements by Jensen et al., 2015.

MODEL VALIDATION

Calibration of the flow model was undertaken using a heuristic approach based on visual inspection of the piezometer levels, statistical performance criteria and general experience of model calibration. Auto-calibration was considered but due to the fact that a model run is very time consuming (approximately 10 hours) it was decided to carry out the calibration manually. Overall the final model reproduced the observed piezometer levels well although peak groundwater levels (and flood levels) were slightly underestimated by 10-15 cm. The simulated groundwater dynamics are shown in Figure 4. The largest discrepancies were observed along transect A in the north-eastern part of the floodplain. This may be due to an underestimation of observed river peak flows and the fact that the model uses daily climate data and stream flow as input but it could also be a result of inaccuracies in the topography or model structure. The model developed by (Poulsen, et al., 2014) similarly struggled to capture peak flood levels which may indicate a problem with the input data, perhaps an underestimation of stream inflows and/or inaccuracies in the topography rather than a problem with the model structure or parameterisation.

The model results in Figure 5 show that during a flood event the floodplain is inundated from the stream by overtopping of the river banks upstream of the transects. The flood water then recedes back into the river to the north of the wetland within 1-2 weeks. Groundwater upwelling however sustains water levels in the peat layer at the surface for up to several months after the event (Figure 4). A sensitivity analysis on vertical conductivity of the peat showed that peak flood levels and the flood recession, are not affected significantly by the connectivity between the surface and aquifer. However, groundwater levels in the peat layer remain higher for longer with lower vertical connectivity. This is likely to affect nitrate reductions with a higher connectivity resulting in more upwelling of water into the peat layer resulting in higher reductions (Jensen et al., 2015). Further work will be required to understand the effects of the vertical connectivity on nitrate retention.

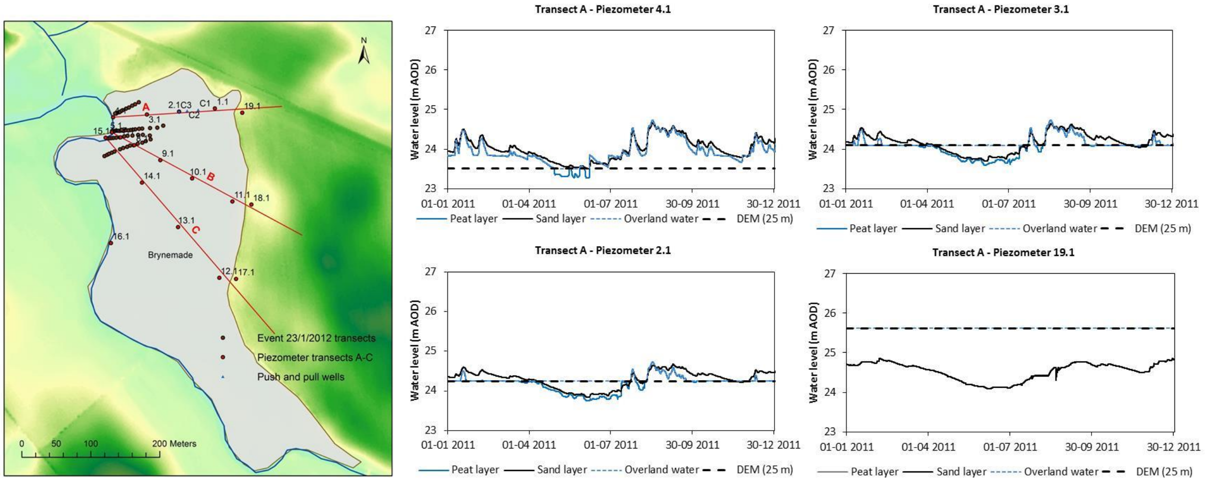

Figure 4: Modelled groundwater levels in the peat and sand aquifer along transect A during wet, medium and dry conditions in 2011

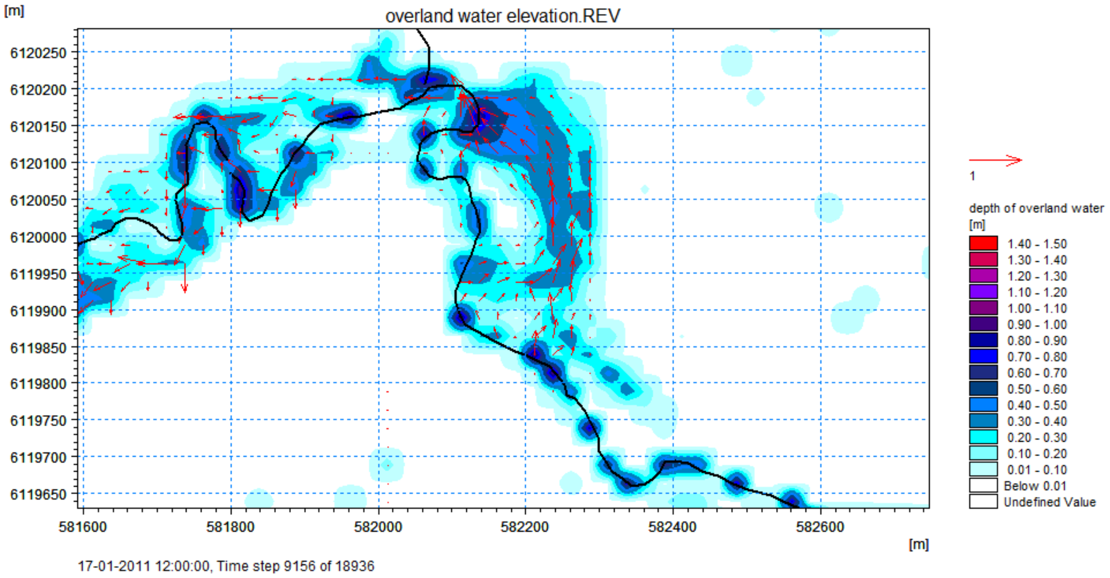

Figure 5: Modelled wetland inundation on 17/1/2011 including flow vectors

WATER QUALITY MODEL

A water quality model for the smaller wetland area shown in grey in Figure 1 was set up in order to test the process descriptions and validate the model against measurements of nitrate and ammonium in the saturated zone along the three transects. The local flow model uses the time varying results from the large model as boundary conditions in order to produce the flow patterns within the small wetland. To be able to represent concentrations at depth the model with nine layers has been used.

Boundary conditions of NO_3-N and NH_4-N were estimated based on the concentrations measured along the edge of the wetland in the piezometers along the three transects using similar values to those used in a transect model by Jensen et al., 2015. Initial concentrations in all compartments were set to 0 mg/l in an initial run and then replaced by equilibrium concentrations at the end of a model run after 8 years. Anoxic conditions have been assumed in the wetland although it is assumed that sufficient oxygen is available to allow for nitrification to occur. Dispersion is included using a longitudinal dispersivity of 1 m and a transversal dispersivity of 0.01 m for both the peat and sand layer, respectively.

Nitrogen process parameters have been estimated based on a combination of values reported by (Jensen et al., 2015) and literature values considered typical for Danish riparian wetlands (Dørge, 1991). The parameters for the overland processes have been estimated based on literature values and are more uncertain. Denitrification and nitrification rates are generally site dependent and can vary substantially between wetlands.

NITRATE REMOVAL

The water quality model captures the movement of the nitrate plume in Transect A (Figure 6) although nitrate concentrations are higher and extend further into the wetland compared to observations. These preliminary model results show that the nitrate plume is not completely attenuated in the wetland but reaches the stream with low nitrate concentrations observed at the river. Removal rates in our model for the wetland area are 61% removal of the nitrate entering the saturated zone (from the boundary and from floodwater), 11% removal of nitrate entering the unsaturated zone and 4.6% removal of nitrate entering the wetland (overland compartment). In terms of total nitrate removal in the wetland area the saturated zone accounts for 13.8%, the unsaturated zone for 0.4% and the overland compartment for 85.8%. This is as expected as the nitrate loads in the floodwaters entering the wetland in the surface compartment are much higher than in the groundwater wetland inflows. As a result more nitrogen enters and is removed from the surface water compartment compared to the sub-surface. Our model indicates that 189 kg NO3-N per year is removed in the saturated zone and 5 kg NO3-N per year in the unsaturated zone compared with 1362 kg/year on the wetland surface. This corresponds to a total of 130 kg/hectare per year which is in line with typical retention rates for Danish wetlands, usually 100-200 kg/hectare per year.

Figure 6 also indicates that nitrate enters the saturated zone from both the stream and agricultural fields. A stagnant zone develops close to the stream due to changing flow gradients causing higher retention times and higher removal rates as discussed also by Jensen et al. (2015). This mechanism will be investigated further in additional model runs. Overall nitrate removal is underestimated in our model compared with field observations. Further work is required to develop an understanding of the main mechanisms for nitrate removal in both the overland compartment and sub-surface of the wetland looking at both flow and water quality parameters.

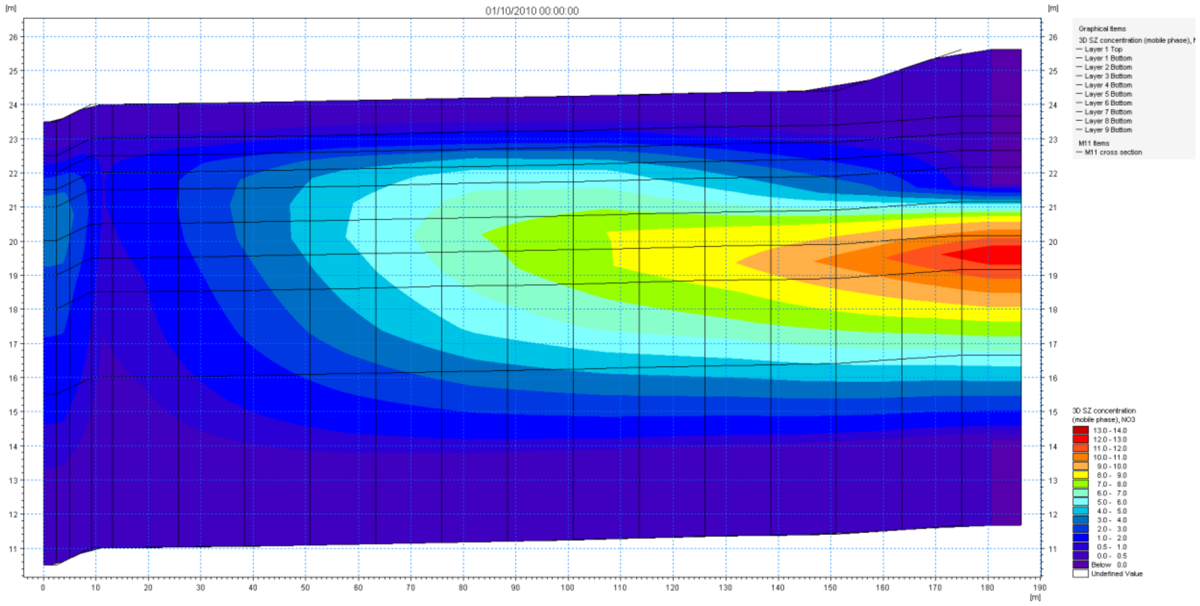

Figure 6: Modelled nitrate concentrations along Transect A on October 1, 2010

SUMMARY

In this study a detailed integrated flow and water quality model has been developed capable of describing the nitrate retention capacities of a riparian wetland on the Odense River, Denmark. Initial model runs demonstrate the applicability of the model for assessing the importance of nitrate processes both on the surface and in deeper sub-surface layers. Based on the preliminary results both nitrate processes in the wetland taking place during surface water flooding and denitrification in the deeper aquifers play an important role in nitrate removal. As expected the actual nitrate removed in the surface compartment is much higher than in the groundwater which indicates that frequent flooding of the wetland is an important mechanism in nitrate removal.

Further modelling work will be undertaken to examine the effects of dispersion, vertical peat conductivities, weed cutting on removal rates and a sensitivity analysis of various process parameters will also be conducted. It is envisaged that some calibration of the N-process parameters and perhaps also soil parameters will be required to improve the match between observations and modelled nitrate concentrations. A comparison with pre-restoration conditions will be undertaken to develop a deeper understanding of actual improvements in nitrate removal rates compared to baseline conditions. It is evident that increased flooding after wetland restoration is of significance. However the effect on denitrification in the deeper sand aquifer is less clear; the preliminary post-restoration model indicates that surface water flooding affects groundwater gradients and creates a stagnant zone beneath the floodplain thereby increasing the residence time for nitrate resulting in an increase in denitrification. Prior to wetland re-construction agricultural drains will have caused higher nitrate leaching to the river and much lower residence times. Finally some work will be undertaken to examine whether these effects can be modelled at a larger scale for the entire re-meandered stream-section at Brynemade.

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