Eco-Hydrological Modelling of Stream Valleys

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PhD Thesis by Ole Munch Johansen - AAU 2011

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by
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PREFACE

The PhD thesis is the result of a 3-year study conducted at the department of Civil Engineering at Aalborg University in Denmark. The project was funded jointly by Aalborg University, the consultancy company NIRAS in Aalborg and the International Research School of Water Resources (FIVA) at the Department of Geography and Geology, University of Copenhagen.

My professional background is a master within Civil Engineering and through my education I have worked with all aspects of Water and Environment from urban hydrology to marine and freshwater recipients and groundwater resources. Combining measurements and modelling for prediction of changes to natural environmental systems is my primary interest. My background has affected the approach to working with eco-hydrological modelling of stream valleys by an “engineering” way of thinking about the problem. In the search for links between altered hydrology and ecological responses the main question has been: *Which hydrological quantities can be measured, modelled and predicted and can these be related to vegetation patterns and functioning of terrestrial ecosystems?* Rather than asking: *How does the ecosystems function and what is the role of hydrology*? It is my perception that this has provided a slightly different outcome than other studies within the same field. A part of the study was conducted in cooperation with the National Environmental Research Institute (NERI) which has greatly contributed to the cross disciplinary aspects in linking the existing knowledge on ecosystem preferences to hydrological quantities.

The thesis is comprised of an introduction and four accompanying papers which have been submitted to international scientific journals. By the end of the study period one of the papers have been published while the rest is under review. The introduction intends to provide a state of the art analysis and at the same time outline the contribution of the individual papers and the PhD as a whole. The appendices are not to be considered as a part of the thesis but they are all related to the subject and were conducted within the course of the PhD study. Some of them are in Danish and summaries and titles are provided in English.

I would to thank my supervisors Jacob Birk Jensen and Morten Lauge Pedersen for numerous of meetings and professional discussions as well as their huge support throughout the study. Thanks to Jacob for the motivation and enthusiasm before the PhD and for the help on establishing relevant contacts and fundraising. I also want to thank NIRAS and Aalborg Utility Company for the collaboration on my main field site near Volsted Plantation and thanks to all students at Aalborg University who contributed to this comprehensive field data set. Finally I want to emphasize the great contribution from my co-authors PhD student Dagmar Kappel Andersen, and Senior Researcher Rasmus Ejrnæs from Department of Wildlife Ecology and Biodiversity, National Environmental Research Institute, University of Aarhus, Denmark. And also a special thanks to Professor Keith J. Beven, Institute of Environmental & Natural Sciences, Lancaster University, UK who has been a great inspiration at PhD courses in Uppsala, Sweden and who still finds time to contribute to the work of PhD students within all aspects of uncertainty in environmental modelling.

Aalborg September 2011 - Ole Munch Johansen

ENGLISH SUMMARY

Predicting the effects of hydrological alterations on terrestrial stream valley ecosystems requires multidisciplinary approaches involving both engineers and ecologists. Groundwater discharge in stream valleys and other lowland areas support a number of species rich ecosystems, and their protection is prioritised worldwide. Protection requires improved knowledge on the functioning of these ecosystems and especially the linkages between vegetation, groundwater discharge and water level conditions are crucial for management applications. Groundwater abstraction affects catchment hydrology and thereby also groundwater discharge. Numerical hydrological modelling has been widely used for evaluation of sustainable groundwater resources and effects of abstraction, however, the importance of local scale heterogeneity becomes increasingly important in the assessment of local damage to these groundwater dependent ecosystems. This calls for new ways of combining measurement techniques and hydrological models working at different scales.

The PhD thesis investigates the hydrological functioning of fen habitats in Denmark by combining detailed field investigations, hydrological modelling and statistical vegetative analyses from a subset of Danish fen habitats. Field investigations elucidated the hydro-geological settings creating the stable calcareous groundwater seepage required by specialised plant communities. The combination of sloping terrain, a high yield groundwater aquifer and relatively low-permeable deposits in the stream valley creates an upward flow direction and the vertical hydraulic gradient is pointed out as a key parameter controlling the groundwater seepage rate. Seepage is difficult to measure directly and an inverse modelling approach is suggested for accurate estimates. The model only requires that the vertical hydraulic gradient is measured over time and moreover it uses precipitation and potential evapotranspiration as inputs. The water level dynamics in groundwater dependent wetlands is concluded to contain valuable information on both soil parameters and seepage rate.

Distributed three-dimensional modelling is required for hydrological impact assessment in relation to groundwater abstraction in wetlands. The heterogenic discharge patterns that often dominate in stream valleys lead to differences in the way areas are affected. Specifically full scale pumping tests have shown a flow reduction in the order of 20 % in a natural spring, whereas no effect could be measured in neither short nor deep piezometers in the river valley 50 m from the spring. Problems of measuring effects of pumping are partly caused by disturbances from natural water level fluctuations. In this aspect numerical models can clearly separate natural variations from a water table lowering induced by pumping.

Water level is the most commonly measured hydrological variable in wetlands. Linkages between the water level regime and fen vegetation is studied for 35 Danish sites. All sites have piezometers installed with continuous registration of water levels, and plant registrations have been conducted in circles around the piezometers. The results show that water table conditions are directly limiting the occurrence of typical fen species, and bryophytes and moreover the analyses provide a rare quantification of the number of species supported by certain water level conditions. Statistical/empirical models are suggested for prediction of typical fen species and bryophytes based on water level and Ellenberg Indicator values which are derived from the vegetation

composition. While the models are useful for identifying environmental conditions limiting the habitat quality, the underlying assumptions might not be valid for prediction of the vegetative response to water level changes, because internal eutrophication is not accounted for.

The results of the study do not support threshold values for groundwater flows or water level conditions to determine significant damage from hydrological impacts. Such threshold values would be a strong simplification of ecosystems which depend on a number of interacting environmental conditions. Improved predictions of chemical changes and nutrient releases after lowering of water tables might be a way to approach meaningful thresholds.

DANISH SUMMARY - SAMMENFATNING

Vurdering af hydrologiske påvirkninger på terrestriske økosystemer i ådale kræver en multidisciplinær tilgang, som involverer både ingeniører og økologer. Grundvandsudstrømning i ådale og lavlandsområder understøtter en række artsrige plantesamfund, hvis beskyttelse prioriteres på verdensplan. Denne beskyttelse kræver øget viden om områdernes understøttende hydrologi og særligt sammenhænge mellem vegetation, grundvandsudstrømning og vand-standsforhold er afgørende for forvaltningen. Vandindvinding påvirker hydrologien i et opland og dermed også den mængde grundvand, som afstrømmer til overfladevandssystemerne. Numerisk hydrologisk modellering anvendes ofte til evaluering af den udnyttelige vandressource og til vurdering af effekterne af vandindvinding, men ved vurdering af påvirkninger på lokale grundvandsafhængige økosystemer øges betydningen af heterogenitet på lokal skala. Dette kræver nye metoder til at kombinere måleteknikker og hydrologiske modeller på forskellig skala.

Denne PhD afhandling undersøger den understøttende hydrologi i rigkærs-habitater i Danmark ved en kombination af feltundersøgelser, hydrologisk modellering og statistiske vegetative analyser i et udvalg af danske rigkær. Feltundersøgelserne har belyst de hydro-geologiske forhold, som skaber en stabil kalkholdig grundvandstilstrømning, der er en forudsætning for specialiserede plante-samfund. Kombinationen af en dybt nedskåret ådal, et højtydende grundvandsmagasin, samt forholdsvis lavpermeable aflejringer i ådalen danner en opadrettet strømning, og den vertikale hydrauliske gradient fremhæves som en nøgleparameter, der kontrollerer udstrømningen. Diffus grundvandsudstrømning er særdeles vanskelig at måle direkte og ny metode som bygger på invers modellering anbefales for at opnå en tilstrækkelig nøjagtighed. Modellen kræver, at den vertikale hydrauliske gradient måles over tid, og som modelinput benyttes desuden nedbør og potentiel fordampning. Det konkluderes desuden at vandstandsdynamikken i rigkær indeholder værdifuld information, som kan anvendes til bestemmelse af udstrømning og hydrauliske parametre.

Distribueret 3D modellering er nødvendig ved risikovurdering af vådområder i forhold til vandindvinding. De heterogene udstrømningsmønstre, som ofte findes i ådale, betyder at påvirkningerne ikke rammer hele ådalen ensartet. Det er specifikt fundet at storskala pumpeforsøg har medført en klar vandføringsreduktion på ca. 20 % i et kildevæld, mens der ikke kunne måles

ændringer i vandstandsforholdene i et rigkær 50 m derfra, hverken i korte eller dybe rør. Problemerne med at måle vandstandsændringen i rigkærene skyldtes delvist de naturlige fluktuationer. Her kan numeriske modeller biddrage ved at separere den naturlige dynamik fra den vandindvindingsrelaterede påvirkning.

Vandstand er den hyppigst målte hydrologiske parameter i vådområder. I dette studie er sammenhænge mellem vandstandsforhold og rigkærsvegetation undersøgt på 35 danske lokaliteter. Alle lokaliteter har piezometerrør installereret med kontinuert registrering af vandstand, og der er foretaget planteregistreringer i cirkler omkring rørene. Resultaterne viser at vandstandsforholdene er direkte begrænsende for forekomsten af typiske rigkærsarter og mosser, og der er opstillet en sjælden kvantitativ sammenhæng mellem antal arter og vandstandsforhold. Statistiske/empiriske modeller er opstillet med henblik på at forudsige antallet af typiske rigkærsarter og mosser baseret på vandstand og vegetationsafledte Ellenberg-værdier. Modellerne er nyttige til at identificere forhold, som begrænser kvaliteten i et rigkær, mens de bagvedliggende antagelser ikke nødvendigvis er gyldige til at forudsige effekter af vandstandsændringer, idet der ikke tages højde for en intern frigivelse af næringsstoffer.

Resultaterne af studiet underbygger ikke fastsættelsen af specifikke grænseværdier for ændret udstrømning eller vandstandsforhold, der medfører en signifikant skadevirkning på grundvands-afhængige terrestriske økosystemer. Sådanne grænseværdier ville medføre en kraftig simplificering af disse habitater, som afhænger af en række interagerende forhold. En øget viden om forudsigelse af vandkemiske ændringer og processer, som styrer næringsstoffrigivelse i jorden efter vandstandsændringer, er nødvendige, hvis meningsfulde grænseværdier skal kunne fastslås.

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Part 1 Introduction

1.1 Background

Groundwater resources

Groundwater constitutes the world's largest available freshwater reservoir and acts as a reliable source of drinking water and water for irrigation. Groundwater also provides important flows to rivers, lakes and wetland ecosystems worldwide. On a global scale approximately 6 % of the groundwater recharge is withdrawn while many countries exploit a far larger share (World Resources Institute 2011). In the North Western Europe countries like Denmark, Germany, The United Kingdom and the Netherlands extract approximately 15-25 % of the annual groundwater recharge while other countries like Belgium, Bulgaria and Portugal abstract between 75 % and 90 % (World Resources Institute 2011). The water pumped from groundwater aquifers will (if not lead back into the system) reduce the amount of groundwater discharging to the surface water systems e.g. wetlands, rivers and lakes and can thereby have an impact on the eco-hydrological functioning of these groundwater dependent ecosystems.

Wetland values

Historically river floodplains have been important to humans as productive grasslands for cattle and as spawning ground for fish (Van Diggelen et al. 2006). Today a large number of ecosystem services are attributed to wetlands and these values are even being expressed in economic terms (Costanza et al. 1997, Rouquette et al. 2009) with increasing political focus. Wetlands act as important carbon storages (House et al. 2010) and drainage of wetlands has a major influence on emission of greenhouse gases contributing to global warming (Ramchunder et al. 2009). Floodplain wetlands play a major role in purifying water (Olde Venterink et al. 2006) and preventing extreme high and low flows to the receiving river ecosystems (Bullock and Acreman 2003). Constructed and semi-natural wetlands are increasingly being thought of as a way of removing nutrients in order to reduce eutrophication of downstream freshwater ecosystems as well as marine end-recipients. Finally biodiversity values within wetlands have recently received an increased focus (Bedford et al. 1999, Hájek et al. 2006, Van Diggelen et al. 2006, Wassen et al. 2005). These mentioned functions (purification, nutrient removal, carbon storage, support of rare species) cannot necessarily be obtained at the same time and there might be conflicts involved in optimising nutrient removal on one side and addressing biodiversity on the other side (Hansson et al. 2005, Singh 2002).Wetlands contain a number of specialised and also endangered species and especially groundwater-fed calcareous fens are among the most species rich ecosystems in the temperate zone (Van Diggelen et al. 2006). Calcareous fens support a variety of specialised plant communities as well as hosting endangered butterflies and molluscs (Stanová et al. 2008).

European legislation

The political focus on biodiversity requires improved knowledge on the human impact on groundwater-dependent terrestrial ecosystems (GWDTEs). In Europe the Water Framework Directive (WFD) (European Communities 2000) and the Groundwater Directive (GD) (European Communities 2006) are working as a driving force in integrated management of water bodies including terrestrial ecosystems which depend on groundwater. This means that GWDTEs must be taken into consideration in the assessment of quantitative and qualitative status of groundwater bodies.

GWDTEs comprise a range of habitats where groundwater plays an important role. Examples are fens, springs, meadows, dune slacks, reed swamps, and alluvial forests. Raised bogs are considered as being completely rainwater fed, however, even though groundwater is not present in the root zone of bogs there is typically some hydraulic contact to an underlying groundwater aquifer and the maintenance of the bog is dependent on a high groundwater table (Glaser et al. 1997). Many GWDTEs are also included in the NATURA 2000 network of areas protected by the Habitats Directive (HD) (European Communities 1992). Assessing significant damage to such terrestrial ecosystems from anthropogenic pressures is a complicated task and the number of potentially affected ecosystems is large. There is a need for both initial screening approaches to determine water bodies at risk (Krause et al. 2007, Whiteman et al. 2010) as well as knowledge and experience on detailed analysis of local scale conditions, e.g. (Kuczyńska 2010), to support decisions regarding societal versus ecosystem needs. Hence addressing European legislation requires application-oriented research.

Hydrology in stream valley wetlands

GWDTEs are typically found in river valleys or coastal discharge areas where groundwater seepage from aquifers takes place (Fig. 1). Often the direct contact between aquifer and the surface water body is limited by low permeable sediments which create a large discharge zone adjacent to the surface water body. The pressurized groundwater aquifer provides a stable seepage that supports a variety of specialised plants.

Groundwater abstraction poses an obvious change to the catchment water balance which affects outflows to these ecosystems. Any amount of water pumped from a river catchment will reduce the discharge to the surface waters accordingly. The impact can be local with a potential large damage or widely distributed resulting in insignificant or little damage to a large area.

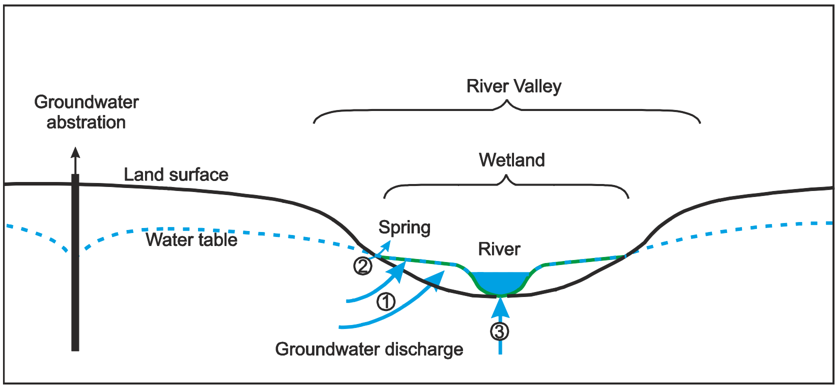

Fig. 1 Cross section of a discharge river valley. Groundwater discharge can occur as a combination of (3) directly to the river (or any surface water body), (1) through the river valley deposits or (2) runoff on the wetland surface with limited contact to organic sediments. Numbering of discharge types follows (Dahl et al. 2007).

Though groundwater discharge mechanisms to dependent terrestrial ecosystems can be complex and diverse some prevailing mechanisms have been reported in the literature. Loon et al. (2009) outlines two different concepts describing groundwater discharge to floodplains. The first mechanism is the *Exfiltration Model* where groundwater discharge is mainly vertically directed throughout the wetland driven by a difference between the pressure head in the underlying aquifer and the surface water table. Evapotranspiration can be a main driver of such seepage. Exfiltration mechanisms have been reported by Fraser et al. (2001), Glaser et al. (1990), Hunt et al. (1996) and Reeve et al. (2006). The second mechanism described by Loon et al. (2009) is the *Throughflow Model,* where groundwater discharge is restricted to the upstream fen margin and redistributed to lower areas closer to the river by flow in the root zone or at the soil surface (Schipper et al. 2007, van Loon et al. 2009, Wassen and Joosten 1996). Common for both perceptions is that groundwater is driven upwards by a vertical hydraulic gradient within the discharge zone. The regional and local hydrological settings supporting such vertical discharge patterns have been investigated by Almendinger and Leete (1998) in six calcareous fens in Minnesota, USA.

A large variability in hydrological settings supporting fen ecosystems has been documented by Grootjans et al. (2006), and there are many other ways groundwater supply to wetlands can occur. It also occurs that the GWDTE is not connected to the primary groundwater aquifer but rather associated with the occurrence of clay lenses or impermeable bedrock on hill slopes. Such settings increase the importance of lateral flow processes. Also highly managed areas e.g. polder systems and artificial channels in the Netherlands can under some circumstances support fen ecosystems, given right environmental conditions (Boeye et al. 1994, Grootjans et al. 2006).

Wetland terminology and ecological gradients

To be able to discuss the role of groundwater in GWDTEs a basic knowledge on mire ecology is required. In terrestrial wetland ecology distinction is made between 1) *permanent wetlands* with a relatively small amplitude of water level fluctuations which do not drive vegetation changes; 2) *seasonal wetlands* where the wetland species are restricted to those that temporarily colonise exposed soils; and 3) *fluctuating wetlands* where long term water level fluctuations (several years) creates phased changes to the vegetation composition (Wheeler 1999). Mires fall into the category of permanent wetlands and they can be defined simply as peat producing ecosystems (Joosten and Clarke 2002).

Three major ecological gradients exist within mire ecology: The alkalinity gradient, the fertility gradient and the water level gradient (Wheeler and Proctor 2000). More than 50 years ago mires were categorised along the pH gradient into bogs with low pH and fens with high pH (du Rietz 1954, Sjörs 1950), and fens were further subdivided into poor and rich fens. Poor fens are nutrient poor while rich fens are rich in their groundwater supply which tends to make them richer in minerals and nutrients, however, not eutrophic. Ombrotrophic (rainwater fed) bogs represent one extreme of the pH-fertility gradient with low pH and low nutrient availability and extremely rich fens defines the other extreme. It can be argued that the extremely rich fens do not even belong to the definition of mires since they are sometimes not peat producing but rather tufa forming (tufa is formed by precipitation of carbonate minerals). Wheeler and Proctor (2000) roughly define bogs as mires with pH<5 and fens as mires with pH >6.

A second ecological gradient, the fertility gradient, controls the productivity in mires which is known to have a major influence on species diversity. While high productive sites tend to be dominated by a few competitive species low productive sites host a larger diversity of specialised and non-competitive species (Wheeler 1999). The terms oligotrophic, mesotrophic and eutrophic are used to distinguish areas along the fertility gradient reflecting the availability of mainly nitrogen and phosphorous (Wheeler and Proctor 2000). The fertility is however not independent of pH and therefore actual measurements of nutrient concentrations may not reflect this fertility gradient for sites within different pH environments. The common perception is that nitrogen enrichment from deposition as well as elevated nitrogen concentrations in the groundwater is a major threat to species diversity in European terrestrial ecosystems (Paulissen et al. 2004, Stevens et al. 2004). However, Wassen et al. (2005) provides evidence that phosphorus should be more widely considered as the limiting nutrient for species diversity in terrestrial freshwater wetlands, even in areas with a very limited nitrogen deposition. Phosphorus limitation is supported by several field studies of fen ecosystems (Boeye et al. 1997, Boyer and Wheeler 1989, Kooijman and Paulissen 2006). A Dutch field study finds that neither nitrogen or phosphorous is likely to be causing eutrophication and suggests an increased focus on potassium in groundwater-fed meadows (Pieterse et al. 2005).

The water level/moisture regime and relations with vegetation composition has been studied by numerous of authors (Grootjans and Ten Klooster 1980, Grootjans et al. 2005, Ilomets et al. 2010, Jabłońska et al. 2011, Lucassen et al. 2005, Mälson et al. 2008b, Runhaar et al. 1997, Runhaar et al. 1996, Van Bodegom et al. 2006, Wassen and Joosten 1996, Wierda et al. 1997). It can be argued that the moisture regime is not a separate factor but rather affects a number of factors such as presence of oxygen, redox conditions, alkalinity and nutrient availability which can completely control the pH and fertility gradients. The range of water level preferences for particular species or communities can be wide and may be affected by a number of other factors which makes it problematic to obtain consistency in linkages between water level and vegetation (Hájek et al. 2006). This will be further discussed in the following sections.

Some disagreement exists on whether fen and bog subtypes should be distinguished based on their physical and chemical preferences (Wheeler and Proctor 2000) or based solely on plant communities (Hájek et al. 2006). Hájek et al. (2006) show that vegetation based subtypes provide the most distinct and comparable subdivisions and they argue that even long term measured environmental data cannot explain the variance in vegetation composition on a large geographical scale. The difficulties in relating the species composition to physical and chemical parameters pose a major obstacle in terms of defining meaningful thresholds according to the European GD and WFD.

The role of groundwater in regulating the water chemistry

The interaction between groundwater and vegetation communities in GWDTEs is governed by complex processes. Most authors agree that groundwater plays an important role, not only in terms of wetness, but in regulation of the water chemistry and the fertility. Water scarcity is not the main issue for fen communities even though some species, especially bryophytes, might suffer directly from drying-out during warm summer periods. Therefore a large amount of research has attempted to unravel some of the mechanisms controlling the water chemistry and much attention has focused on the increased fertility as a result of human pressure on land use and on the hydrological cycle.

In GWDTEs nitrogen can be provided directly by groundwater discharge in the form of nitrate causing eutrophication (Drexler and Bedford 2002). Phosphorus is mostly bound to clay minerals, organic matter or iron complexes in the soil and hence the eutrophication with phosphorus is not related directly to groundwater inflows but rather to internal releases, which may indirectly be regulated by groundwater inflows.

Stable water table conditions are regarded as a prerequisite for the high species diversity in natural rich fens (Almendinger and Leete 1998, Boomer and Bedford 2008) and drainage and lowering of the water table have been reported to increase the nitrogen and phosphorous availability by mineralisation of peat (Kettunen et al. 1999, Wassen and Joosten 1996). However in managed fens release of phosphorous becomes a great problem when it is attempted to compensate hydrological changes by artificial flooding by surface water or damming. Severe *internal eutrophication* by phosphorus has been reported as the result of preventing drought in heavily managed wetlands in the Netherlands by artificial flooding during summer periods (Roelofs 1991, Smolders and Roelofs 1993). *Internal eutrophication* is a phenomenon which occurs, when the binding capacity of the sediments is reduced (Smolders et al. 2006). Phosphorus is typically bound to oxidised iron complexes but also calcium is reported to have phosphorus binding capacities in lakes and shallow freshwater systems (Boyer and Wheeler 1989, Golterman 1997, Moore Jr. and Reddy 1994). High sulphate content in the surface water interferes with the iron-phosphate cycle and reduces the phosphorous binding capacity of the sediment (Smolders et al. 2006). In such cases short periods of drought and the presence of nitrate can benefit the ecosystem by oxidation of iron and hence preventing sulphate induced phosphorous release (Lucassen et al. 2004, Lucassen et al. 2005).

The alkalinity further plays an important role in regulating phosphorous availability. Higher alkalinity result in a higher phosphorous availability due to elevated decomposition rates and because bicarbonate competes with phosphate for anion adsorption sites (Smolders et al. 2006). The external supply of alkalinity is directly related to the calcium and magnesium content in the groundwater. However, alkalinity is also generated internally by reduction of nitrate, sulphate and iron-oxides present in the soil-water (Boomer and Bedford 2008, Smolders et al. 2006).

Groundwater seepage rates and water table fluctuations are negatively correlated; hence a high seepage rate can ensure a relatively stable water table and a constant surplus of groundwater (Cirkel et al. 2010). Almendinger and Leete (1998) states that calcareous fens may need water tables sustained near the peat surface by large vertical ground-water discharges to allow carbonate precipitation, which is associated with the rare fen vegetation. The water table only drops in periods where the groundwater supply is smaller than the evapotranspiration. The position of the water table controls the redox conditions which in combination with the nutrients and alkalinity transported by groundwater have a major influence on all three ecological gradients pH, fertility and wetness. But since eutrophication can be a result of both low and (artificial) high water tables and since the processes reported to trigger eutrophication might differ from site to site it still remains a question whether optimal hydrological conditions can be defined and how sensitive the habitats are towards changes in water level and groundwater fluxes.

Water level and vegetation relations

Links between water level and vegetation composition undoubtedly exist. The hypothesis is simple and obvious however little conclusive evidence and limited consistency has been reported (Wheeler 1999). Nevertheless it seems necessary to establish some direct linkages because water level changes can be accurately measured and predicted using hydrological models, while chemical responses are considered unpredictable.

Below some aspects are highlighted which are believed to be the major obstacles in obtaining clear water level preferences for plant species and communities.

- Sites investigated are typically assumed to be in equilibrium which is difficult to verify since changes to the hydrological regime can occur fast while the vegetative response is slow (years or even decades). Therefore there is a risk that vegetation does not reflect the current state of the wetland (Ertsen et al. 1998, Wheeler 1999).
- Vegetation depends on soil moisture which is affected by soil texture and capillary rice and to some extend the water table depth. Especially for semi-dry conditions water level is not the best measure of wetness in the root zone (Hunt et al. 1999, Schaffers and Sýkora 2000).
- Several other conditions may affect the vegetation dependency on water levels by changing the competition between species (Hájek et al. 2006).
    - Soil-water chemistry in general (alkalinity and fertility)
    - Management practices such as grazing, cutting or burning
- Using a large number of sites to describe a vegetation shift along a water level gradient does not automatically provide models to predict the effects of lowering the water table. Using such *space-for-time substitution* in diverse and possibly disturbed ecosystems can be problematic (Walker et al. 2010).

Many examples of quantitative studies on water table-vegetation relations exist. Almost 40 years ago Niemann (1973) studied patterns of water table fluctuations and plant communities using more than 600 water level gauges. Niemann (1973) found that the shape of so called *duration lines* (cumulative distribution of water level depth) reflected the rate of groundwater discharge. Grootjans (1980) made a thorough characterisation of water level regimes in drained and undisturbed meadows in the Netherlands using the ideas of Niemann and he showed that drainage significantly changed patterns of *duration lines* and lowered the species diversity in the following years after drainage. Well documented research has shown how drainage or groundwater abstraction has led to a decline in biodiversity, however, these studies are conducted in areas where a dramatic lowering of the water table has taken place (Grootjans et al. 1988, Grootjans et al. 2005, Harding 1993, Mälson et al. 2008a) and the following degradation of the habitats was not related to the quantity of water level changes. This makes the results difficult to use for prediction in other areas.

Ertsen et al. (1998) and Runhaar et al. (1997) established quantitative relations between water level and the Ellenberg moisture score (Ellenberg 1991) for a range of Dutch wetland habitats. Using plant indicator scores provides a large statistical foundation which can be used to establish response curves for individual species e.g. (Horsák et al. 2007, Štechová et al. 2008) or species communities (Wamelink et al. 2002). However, these indicator scores must be reasonable predictors of environmental conditions which seem not always the case (Wamelink et al. 2002). The Ellenberg Indicator system is further described in the following section. (Runhaar et al. 1997) showed significant relations between water levels and the relative number and cover of species preferring wet conditions. The purpose of the study by (Runhaar et al. 1997) was to establish an ecologically relevant classification of sites according to the moisture regime. Their study therefore covered a broad range of habitats along the wetness gradient. There is, however, not an obvious link to species diversity and habitat quality in such classification.

Investigations have attempted to determine which water level measures are most important in controlling vegetation patterns in mires. Typically minimum, mean, maximum, annual amplitude or seasonal water levels are examined. Hájková and Hájek (2004) studied water level preferences for individual sphagnum species in Western Carpathians mires and found that maximum water levels were significantly correlated to the presence of bryophytes. Wierda et al. (1997) also found highest water levels to be more important than lower levels in a study based on wet meadow communities in areas where inundation played an important role. Jabłońska et al. (2011) examined differences in water level preferences for eight major mire-vegetation types found in the Rospuda Valley in Poland. They found that only tall sedge-reed and alder woodlands were controlled by highest water levels, while both sphagnum and brown moss dominated communities were controlled by lowest water levels or the annual variability. It is important to clarify these differences when it comes to evaluating the effect of groundwater abstraction. The minimum water level and the annual variability are likely affected by local alterations such a pumping from the aquifer, while maximum water levels and flooding incidents are more likely to depend on extreme precipitation and runoff characteristics in the catchment.

Eco-hydrological modelling

Two main branches of eco-hydrological studies exist. On that deals with vegetation structure and the spatial patterns related to dynamics in hydrological processes and another that deals with biodiversity and the links between species/community occurrence and hydrology. I will here briefly explain the concepts of eco-hydrological model approaches addressing biodiversity and ecological impact assessments with respect to water management. Such models have primarily been developed in the Netherlands. Three types of model techniques can be distinguished: 1) models based on expert knowledge; 2) empirical statistical models; 3) Mechanistic models. Expert knowledge based models typically involve the use of ranking lists e.g. (Ellenberg 1991), where plant species have been assigned indicator values along environmental gradients such as moisture, alkalinity, light, salinity and fertility. The values are based on expert knowledge and experience and ordinal scales are used (Venterink and Wassen 1997). Empirical statistical models are “black box” models where relations between hydrology (quantitative and qualitative measures) and vegetation occurrence is based on statistical analysis with no attempt to explain the underlying physical, biological or chemical processes. Finally mechanistic models deal with the involved processes by applying more well-established chemical and physical laws. In an area where the causal relationships are complex and not fully understood all of these approaches have advantages and disadvantages.

Models based on plant indicator values (expert judgement) are superior to other approaches by the large amount of available data. Plant registrations are conducted more widely than measurements of environmental variables and the occurrence of species is a highly comparable and relatively stable measure reflecting the long-term environmental conditions. The disadvantage is the link to environmental conditions which despite calibration attempts e.g. (Ertsen et al. 1998) seem to remain highly scattered. An example of a model based on expert judgement is Gremmen et al. (1990), who provide a step by step assessment tool based on Ellenberg indicator values combined with subjectively chosen thresholds. The inputs are 1) the estimated lowering of the groundwater table and 2) the annual soil moisture deficit. The model further requires knowledge on the soil nutrient release in relation to drainage. The model output is a probability of disappearance of species with certain Ellenberg F scores. The model is highly operational however also highly subjective and coarse in the selection of thresholds. A Danish study shows a promising link between Ellenberg Indicator scores and nature conservation status in Danish alkaline springs and fens (Andersen and Ejrnæs submitted 2011). The same study also concludes that Ellenberg F (moisture score) does not contribute as an explanatory variable with respect to conservation status in Danish fens and springs and thereby indicates a weak indirect link between vegetation and hydrology.

An example of an empirical-statistical model is the HYVEG model (Noest 1994b) developed to predict the effect of groundwater abstraction in Dutch dune slacks. The model was based mainly on quantitative hydrologic data but also climatic data and site characteristics. The most significant explanatory variables were identified and used in logistic regression of 100 dune slack species. A large number of parameters go into the model and for proper predictive capability parameter values must be supported by a substantial amount of abiotic field data. A similar concept is developed in the ITORS (Influence Terrestrial site conditions On the Response of Species) model (Ertsen et al. 1995), where influences of changed water quality are also taken into account.

Examples of mechanistic models in eco-hydrological studies are mainly associated with hydrological or soil-chemical models. Examples are 2D or 3D groundwater models (Boswell and Olyphant 2007, van Loon et al. 2009) or 1D or 2D unsaturated zone models (Cirkel et al. 2010, Schot et al. 2004). These models can deliver a hydrological input to a stand-alone empirical ecological model. Mechanistic models are generally considered stronger in predictive capability compared to statistical-empirical models used in ecology (Fujita et al. 2007). Hydrological modelling is a widely used tool for addressing the effect of pumping on a large scale (catchment or sub-catchment scale) and both lumped and distributed based models have proven capable of predicting outflows to river systems given that the hydrological and geological information is sufficient. Numerous examples exist where hydrological models are successful in predicting large scale processes despite the fact that local scale heterogeneity has not been resolved (Refsgaard et al. 2010). However, complexity increases when predictions of local discharge patterns are needed, and the many parameters to be determined are rarely supported by the amount of data available. Moreover groundwater and surface-water interactions can be controlled by non-linear flow processes and thresholds (Beven and Kirkby 1979, Van Der Velde et al. 2009) which might require highly detailed mapping and intensive data collection on a local scale. Moreover attempts have been made to capture the essential chemical processes which are relevant to fen ecology and incorporating these in mechanistic models. Kemmers et al. (2003) used the model ECOSAT (Equilibrium Calculation of Speciation And Transport) (Keizer and Van Riemsdijk 1996) as a tool for identifying key chemical components and processes in base regulation of rich fen systems. For this purpose the groundwater flux and the chemical composition of groundwater and soil was measured or estimated. Some components, e.g. nitrates, were ignored and since ECOSAT is based on equilibrium concentrations the effect of dynamic changes in redox conditions etc. was not fully taken into account. Chemical speciation modelling was concluded to be a useful tool for interpretation of processes in fen chemistry (Kemmers et al. 2003). No examples have been found where chemical modelling was used directly in prediction of pH/nutrient changes induced by changes in groundwater inflow or water table lowering.

A problem in many eco-hydrological models predicting biodiversity is that only equilibrium states are modelled, and vegetation is assumed to reflect the site conditions. No succession from one equilibrium state to another is modelled and no short term eutrophication effects are taken into account because of the unpredictable nature or (hopefully) simply a lack of understanding of short term nutrient dynamics and its eutrophication effect in wet terrestrial ecosystems. Hence the essential time-lag between site conditions and vegetation is often ignored because it cannot be determined.

1.2 Problem definition and objectives

The overall objective of the study was to improve predictions of hydrological changes in groundwater dependent terrestrial ecosystems as well as elucidating hydrology-vegetation relations. The use of scientific-based models to support decision making has not been a tradition in Denmark despite a long tradition of groundwater based drinking water supply and despite the large amount of related research especially in Holland during the last decades. However EU and national policies require that decisions are made and research is needed to provide both scientific and operational knowledge in interactions between hydrology and vegetation in wetlands.

The main objective has been addressed through four specific objectives:

- To study the groundwater supply mechanisms and discharge patterns through field studies in Danish stream valleys, *Papers I* and *IV*
- To investigate the possibilities of hydrological modelling of GWDTEs on an ecologically relevant scale, *Papers II* and *IV*
- To develop methods for quantifying groundwater discharge to ecosystems, *Papers I* and *II*

- To relate hydrological and/or chemical quantities to vegetation communities in GWDTEs, *Papers I*,*III* and *IV*

The scientific papers all have their main focus on Danish fen ecosystems, though it was not the overall intention of the study to deal with one certain habitat type. This has, however, been a natural choice since fens are considered highly sensitive towards changes in groundwater hydrology and Danish monitoring activities are much more concentrated on fens than e.g. humid dune slacks.

1.3 Landscape, groundwater abstraction and groundwater dependent terrestrial ecosystems in Denmark

A variety of landscape settings are known to support groundwater fed terrestrial ecosystems including both natural and highly managed areas (Grootjans et al. 2006, Jansen et al. 2000). In Denmark stable groundwater flows are typically associated with discharge areas in stream valleys. Many streams are located in sloping moraine landscapes and are connected to regional aquifers which support seasonal stability of groundwater flows (Almendinger and Leete 1998, Dahl et al. 2007). During the latest glacial period (Weichsel ending approx. 10,000 years BC) Denmark was located on the line of the maximum ice progression which has created a varied landscape with regional differences in topography and dominating soil types. A simplified classification of Danish landscapes is shown on Fig. 2 – upper figure.

Loamy soils are mainly found on the islands Zealand and Funen and in the eastern part of the Jutland while large areas in northern Jutland and in particular western Jutland are dominated by sandy soils. The Quaternary limestone deposits are near the surface in central parts of Jutland and most of Zealand and they may play an important role in supporting alkaline habitats. The net precipitation varies from around 800 mm year^{-1} in western Denmark to around 200 mm year^{-1} in the eastern part due to differences in both precipitation and evapotranspiration within the country (Henriksen and Sonnenborg 2003).

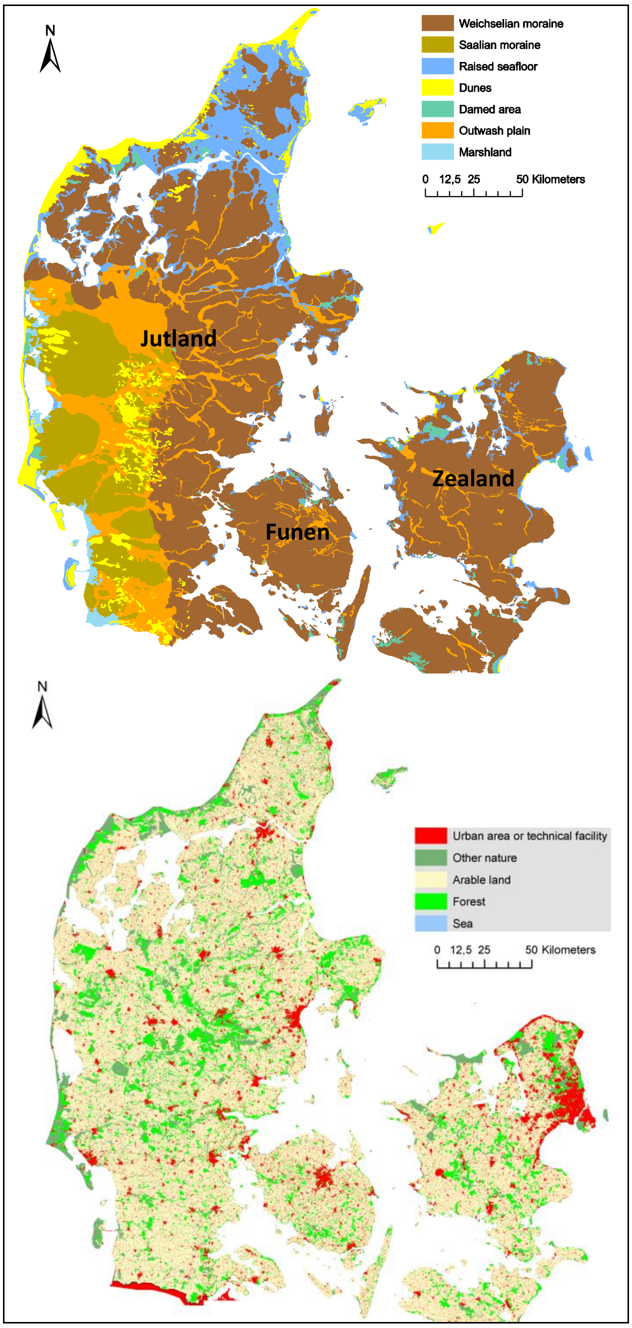

Fig. 2. Simplified landscapes (upper) and land use (lower) in Denmark. Data sources: DJF (Danmarks Jordbrugsforskning – soil cover maps) and NERI (National environmental research institute – Areal Information System – AIS)

Roughly 66% of the country is arable land while forest and other dry and wet nature areas constitute 21 % of the area in total (Fig. 2 lower). Besides the direct conversion from nature to agricultural land, eutrophication is believed to be responsible for the loss of biodiversity in both wet and dry habitats. However, also severe fragmentation and lack of connection between areas of undisturbed nature is a main problem. Comprehensive action plans for protection of the aquatic environment has been implemented in 1987, 1998 and 2003 aiming at reducing the phosphorus and nitrogen loading to the environment. The legislation is now slowly beginning to have a positive effect on nitrate in groundwater aquifers, rivers and lakes throughout the country. Biodiversity is however still declining and especially open nature adapted to nutrient poor conditions is under pressure (Ejrnæs et al. 2011).

Denmark has a long tradition for abstraction of groundwater for drinking water and irrigation purposes and there are suitable aquifers in all regions of the country. 97 % of all drinking water comes from groundwater (2005 figures) and the water is largely untreated before distribution (Thorling et al. 2009). It is estimated that the total permission for groundwater abstraction equals the sustainable resource as an average for the country based on figures from year 2000 (Henriksen and Sonnenborg 2003). The sustainable resource was evaluated through model simulations by a national groundwater model – *the DK-model* (Henriksen et al. 2003) with fairly accurate estimates of groundwater recharge and runoff in the larger river systems. A general overexploitation takes place in some regions, especially in northern Zealand but possibly also in regions in Jutland depending on the highly variable abstraction for agricultural purposes. Hence a large number of abstraction wells possibly affect GWDTEs in Denmark on local a scale.

The location of wet terrestrial ecosystems in Denmark is shown on Fig. 3. Based on numbers from the public NATURA 2000 database (European Communities 2011), the occurrence compared to total European presence can be summarised as follows: humid dune slacks: 8,000 ha (27 % of the total European area); alkaline fens: 9,000 ha (6.5 % of total European area); meadows: 10,000 ha (6 % of total European area) and active bogs: 3,000 ha (0.7 % of total European area). The dune slack areas are located along the west coast of Jutland. Fen habitats are typically located in the stream valleys or in discharge zones adjacent to fjords or lakes, and they are fragmented and isolated due to drainage and land use history. Bogs are found in depressions in elevated parts of the landscape or on flat marine deposits in the lowland with no or little contact to the groundwater.

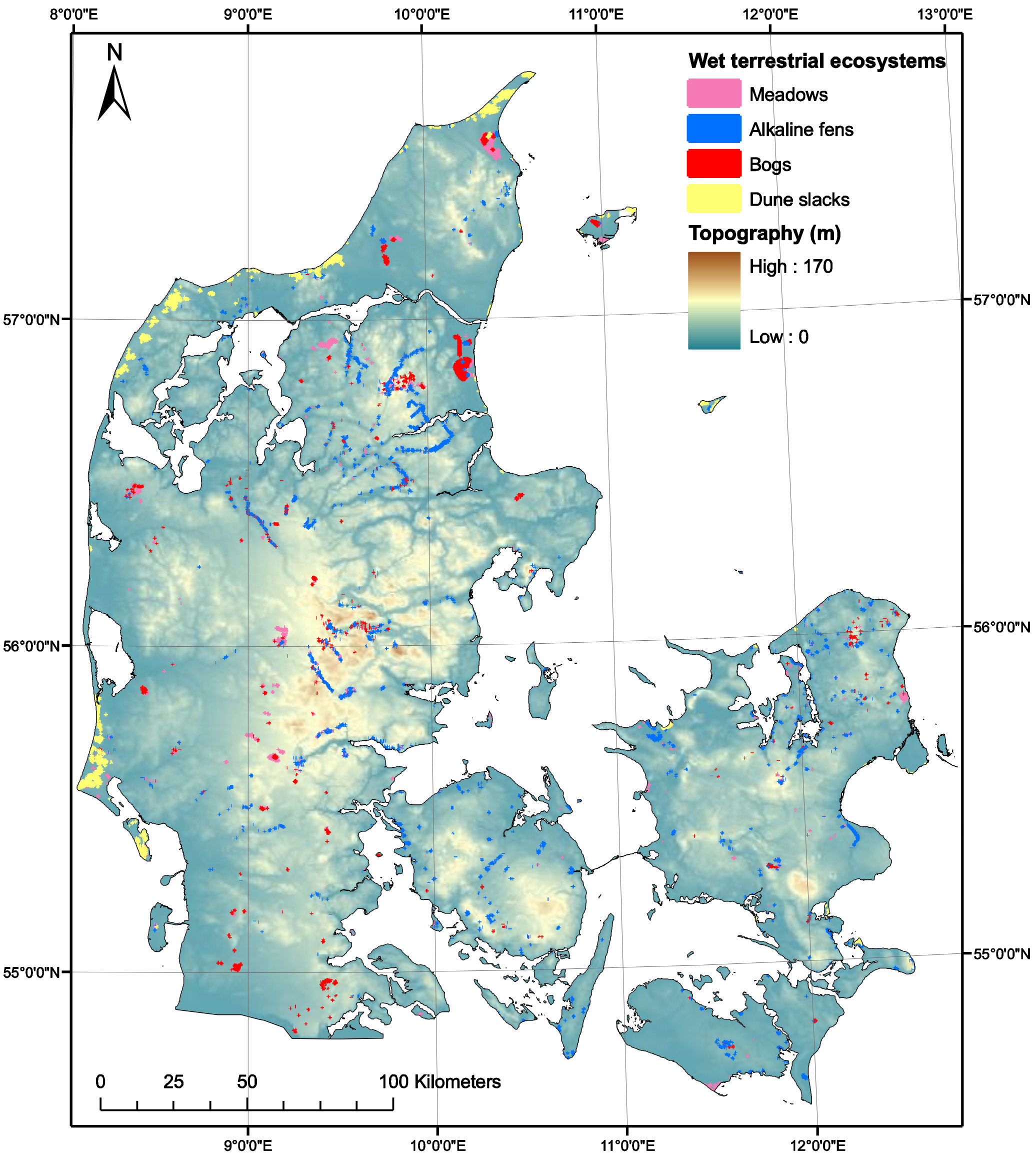

Fig. 3. Location of wet terrestrial ecosystems in Denmark with topographic variations in the background. The size of each habitat is exaggerated on the map.

1.4 EFFECTS OF HYDROLOGICAL ALTERATIONS IN DANISH FEN ECOSYSTEMS

This section summarises the ideas, approaches and contribution of the PhD. Most of the work has been presented in the four scientific papers which comprises the main part of the thesis. Firstly the highlights and main conclusions of each paper are briefly stated, because I find, that this provides a necessary overview to the reader. This is followed by a discussion on the main topics covered by one or more papers within the study. Finally perspectives and suggestions to further research are addressed.

Paper I: Effect of groundwater abstraction on fen ecosystems

The paper presents analyses conducted at the main field site in Lindenborg river valley in the northern part of Denmark. The municipal water supply company investigates the possibilities of abstracting groundwater for drinking water near the NATURA 2000 area. Results from an intensive monitoring programme and full scale pumping tests are presented along with hypotheses on the hydrological processes supporting the fen habitats. Main conclusions:

- The combination of low-permeable deposits in the river valley and a high yield aquifer creates a stable discharge to fen ecosystems.
- The hydrological setting creates a steep upward hydraulic gradient at the fen margin driving groundwater seepage through the low-permeable deposits.
- Natural springs occur in the absence of low-permeable deposits.
- Monitoring during pumping test showed no measureable effect on water levels in the fen habitats, while flow in nearby natural springs was clearly affected.

Paper II: Quantification of seepage in groundwater dependent wetlands

A method for quantifying seepage rates by inverse hydrological modelling is presented. Water level time series from a short and a deep piezometer is used to constrain the hydraulic properties along a 1D profile of the soil. The water balance is closed by describing runoff near the surface, seepage at the lower boundary and by using precipitation and estimates of potential evapotranspiration as forcing inputs at the upper model boundary. Main conclusions:

- Water level dynamics contains information on seepage rate and soil parameters in discharge areas
- Water level is affected by micro-topography and heterogenic peat structures near the surface which is not easily taken into account in a model based solely on Richard's Equations. These effects can be described by a lumped model.
- Inverse modelling appears to be a robust method to determine seepage in discharge zones.
- Determining the seepage rate in a large number of habitats might be important to improve water-vegetation relations

- The results have the potential to improve models including chemical processes in groundwater dependent wetlands

Paper III: Relations between vegetation and water level in fens

The paper investigates relations between water level and occurrence of vegetation species in 35 Danish fens. A set of parameters were derived from the water level and vegetation data respectively and their mutual correlations were determined. Statistical models for predicting the number of typical fen species and bryophytes were proposed. Main conclusions:

- Water level conditions are directly limiting the number of typical fen species and the bryophyte diversity in fens.
- The best habitat quality was found at sites with mean water levels less than 10 cm below ground and extreme water levels no more than 50 cm below ground.
- Optimal water level conditions are no guaranty for occurrence of specialised, seepage dependent plants. Low nutrient availability and neutral or high pH values are required in combination with stable water levels to sustain typical fen vegetation.

Paper IV: From groundwater abstraction to vegetative response in terrestrial ecosystems – an example from Denmark

A distributed hydrological model including saturated zone, unsaturated zone and surface runoff processes was setup and calibrated against the comprehensive dataset presented in *Paper I* in order to predict the consequences of groundwater abstraction on fen ecosystems. Main conclusions:

- Hydrological modelling of abstraction related consequences on GWDTEs in river valleys requires a high spatial resolution. While 25 by 25 m grid cells were sufficient to predict changes in aquifer pressure head in the river valley, a 5 by5 m grid was required to obtain an acceptable description of the fen water table.
- Abstraction reduces the seepage rate to fens in wet periods and lowers the water table in dry periods.
- The presence of a natural spring keeps the surrounding pressure head constant which minimizes the effect of abstraction on a nearby fen.
- Abstraction of 1 mill. m^3 pr. year at a distance of 1km lowers the fen water table by 2-3 cm in summer periods. This corresponds to a 10 % increase of the water table depth
- The change in water level will not in itself lead to a significant change in vegetation composition.
- Results indicate no significant change in water chemistry or nutrient release because the imposed water level change is small compared to natural variations.

Fen hydrology

Paper I addresses groundwater supply mechanisms in Lindenborg river valley in Northern Denmark. The specific study site is located in a NATURA 2000 area where a high yield limestone aquifer and low-permeable river valley deposits support the occurrence of a large number of alkaline fens and springs along the Lindenborg River. The groundwater aquifer in the area further provides ideal settings for abstraction of drinking water and since 2005 the municipal water supply company has investigated the possibilities of placing a new well field near the river valley. This potential conflict between abstraction and groundwater dependent habitats defines the central problem in the thesis and the on-going field survey has provided a unique dataset to support the research objectives in all four scientific papers.

The data collected in Lindenborg river valley was used to estimate the water balance in terms of inflow and outflow to a fen area and to evaluate hypotheses on the route of groundwater seepage entering the fen. It was concluded that the fen is located in a discharge zone where vertical flow paths dominate while horizontal inflows to the upper peat along the fen margin are negligible. Such vertical discharge pattern along the edge of a river valley is very often present on the interface between a high permeable aquifer and low permeable river valley deposits, which is supported by investigated hypotheses in Loon et al. (2009) and other field studies (Almendinger and Leete 1998, Fraser et al. 2001, Glaser et al. 1990, Hunt et al. 1996, Reeve et al. 2006). The interesting aspect of this conclusion is that a vertical seepage rate is easier studied than horizontal flows near the surface. This is because horizontal water movement takes place near or at the surface of the peat where it is controlled by highly heterogenic hydraulic properties, micro topography and non-linear flow processes. Vertical flows on the other hand are much more likely to be described by a simple Darcy flow, where the flow rate is proportional to the hydraulic gradient. Measurements of hydraulic gradient are reliable and easy to conduct. By placing both deep and short piezometers in the river valley valuable information was obtained on the dynamics of groundwater seepage and the effects of precipitation and evapotranspiration. The magnitude of groundwater seepage remained uncertain in the work presented in *Paper I* because of the difficulties involved in determining the effective vertical hydraulic conductivity. It was attempted to measure surface runoff in surrounding ditches to close the water balance and quantify the groundwater seepage, however, the uncertainties involved in the measurements and underlying assumptions only allowed a rough estimate of the seepage.

Seepage

The seepage rate is believed to be more closely related to seepage dependent plant communities than water level and it is therefore an important parameter which is highly difficult to measure directly. It was attempted within the PhD to use heat as a tracer to estimate seepage fluxes in discharge wetlands. The differences between groundwater temperature and temperatures at the surface means that heat is conducted vertically though the water-soil matrix. Water movement caused by seepage or infiltration fluxes affects the subsurface temperature profile. This has been used to determine hydraulic properties and vertical groundwater flow beneath streams (Lapham 1989). Two ideas were investigated using the same approach in groundwater dependent wetlands. The ideas and preliminary results are described in appendix VI. It was concluded that uncertainties of the method were large and further elucidation would be required in order to obtain useful results in an eco-hydrological perspective. While boundary conditions for the method are well defined for streams and lakes, this proved not to be the case in terrestrial wetlands.

The problem of measuring seepage lead to the idea of using the information captured in the water level records in both deep and short piezometers to constrain the effective hydraulic conductivity and thereby determine the seepage rate (*Paper II*). A similar idea was presented by Cirkel et al. (2010) who adapted the original idea from Bloemen (1968). Also Hunt et al. (1999) concluded that seepage had a significant effect on the water level conditions. We showed that a physically based 1D model solving Richard's equations was not adequate to describe the effect of lateral flow processes near the surface, where the peat characteristics change dramatically. Therefore it was preferred to apply a much simpler mass balance concept with less parameters and simple empirical functions to describe surface runoff and variability in effective porosity. The simple model concept showed an increased capability to capture water level dynamics and still support narrow seepage prediction limits. This allows seepage dynamics to be determined with high accuracy (+/- 1 mm) given that the precipitation, evapotranspiration and vertical hydraulic gradient of a site are known. The concept is only valid if the groundwater inflow is proportional to the vertical hydraulic gradient. Referring to the experiences from this study as well as groundwater supply mechanisms described by Loon et al. (2009) and Almendinger and Leete (1998), the assumption is likely to hold for seepage areas that contain a combination of a high permeable aquifer and low permeable deposits near the surface. If a horizontal redistribution of groundwater occurs near the surface, the proportionality between groundwater inflow and the vertical pressure gradient will be non-linear, however it will still exist. Therefore the model might still be produce useful estimates in areas, where some horizontal movement of groundwater occurs. On the other hand the concept fails, if only a small and insignificant vertical gradient is present.

In this study seepage was estimated at the same location by four different approaches: 1) as the remaining term in the water balance; 2) by annual temperature variability in piezometers, see also appendix VI; 3) by inverse modelling using water level dynamics to constrain the hydraulic conductivity; 4) by 3D distributed modelling. Table 1 summarises the results. In the water balance approach (*Paper I*) flow in ditches was assumed to originate from seepage through the fen area, whereas some might be groundwater discharged directly to the ditch or runoff generated by precipitation events prior to the measurements, which could explain an overestimation.

Table 1. Estimated seepage rates in a discharge fen by different approaches. *Qualitative indication of uncertainty.

Method	Seepage rate	Scale	Source	Uncertainty
Water balance	11 mm day^{-1}	50 m x100 m area	*Paper I*	high*
Temperature measurements	7 mm day^{-1}	point	unpublished	medium-high*
1D UZ modelling	2,9 mm day^{-1}	point	*Paper III*	+/- 1 mm
3D distributed modelling	3,5 mm day^{-1}	5 m x 5 m cells	*Paper IV*	low*

In development of indirect seepage estimation it will be important to verify the model approaches with accurate measurements of the seepage rate. Ingram et al. (2001) describes a lysimeter design for direct measurement of net seepage/infiltration in mires, which should be considered. Other reported approaches are based on indirect measurements using natural or introduced tracer's e.g. temperature, chloride or isotope methods e.g. (Anderson 2005, Hunt et al. 1996). The perception that seepage is more decisive for vegetation composition in GWDTEs than water level has not been studied further because of limited supportive data for Danish habitats. However the National Monitoring Programme has recently been restructured to include registration of the vertical hydraulic gradient in groundwater dependent habitats.

Water level in Danish terrestrial ecosystems

This section presents a few additional analyses on water level time series from Danish terrestrial ecosystems, whereas only data from fens have been presented in the scientific papers. Water level dynamics has a major effect on vegetation composition in GWDTEs and it is the most commonly measured hydrological variable, because flows are difficult to measure and soil moisture content is less comparable across sites. The water level is dependent on a number of factors; precipitation, evapotranspiration, groundwater inflow, lateral fluxes, surface runoff, micro topography and soil properties.

Within the study a broad selection of water level time series from Danish meadows, bogs, fens and forest wetlands has been collected and analysed. Both managed and undisturbed sites are present in the dataset. The origin of the data is primarily the National Danish Monitoring Programme (NOVANA), but also data collected as a part of unpublished case studies (Ejrnæs et al. unpublished note 2010, Johansen et al. 2011). In order to describe and compare the observed water level regimes the inner quartile range (*IQR*), see also Hunt et al. (1999), was calculated for each time series and data from meadows, fens, bogs and woodlands is compared in Fig. 4. As expected fens have the most stable water table due to groundwater inflow (Hunt et al. 1999). Even though residence time curves for bogs and fens seem very similar, the boxplot on Fig. 4 shows that *IQR* is significantly different for fens (median = 8 cm) vs. meadows (median = 24 cm) and fens (median = 8 cm) vs. bogs (median = 16 cm).

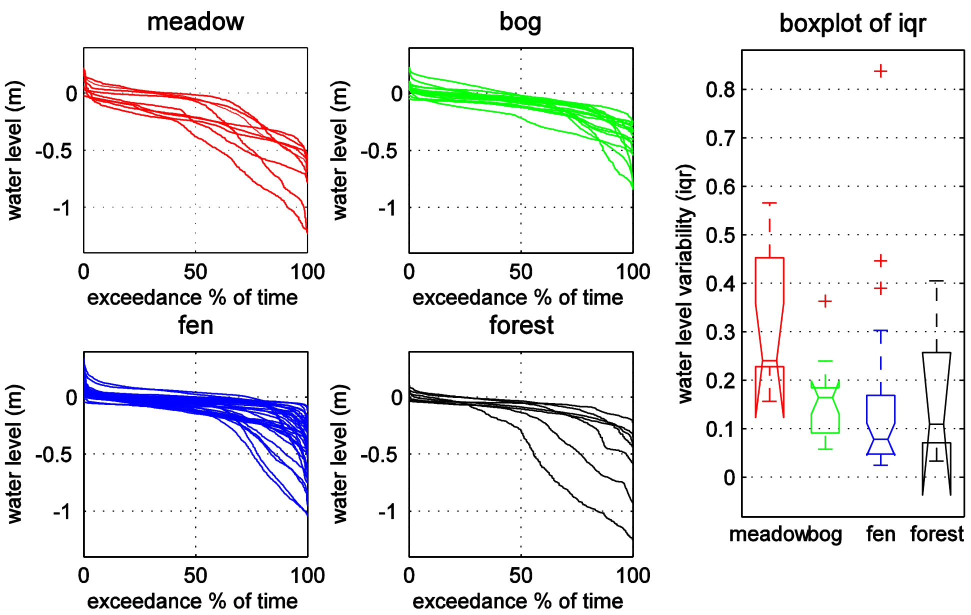

Fig. 4. Water table residence time curves for meadows, bogs, fens and forest wetlands in Denmark. Y-axis represents the percentage of time where the water level is below a certain level. The water levels are relative to the terrain hence positive during flooded situations and negative for water levels below the terrain. Terrain levels are generally uncertain in the data set. On the right a boxplot shows the inner quartile range (*IQR*) of each water level time series belonging to meadow, bog, fen or forest habitats

The studies of Niemann (1973) identified three shapes of *duration lines* (identical to our *residence time curves*) and it was stated that the shape reflects groundwater inflow as follows: 1) Concave (mean<median) curves point to infiltration of precipitation in wet seasons. Convex (mean>median) curves point to large groundwater supply. 3) Sigmoid (s-shapes) lines point to effects of superficial drainage (Grootjans and Ten Klooster 1980).

The hypotheses 1) and 2) were tested using our dataset, but no significant differences were found in the ratio mean/median for meadows, bogs, fens or forests. Differences were expected for bogs vs. fens if the shape of *duration lines* was directly associated with groundwater inflows. While the studies of Grootjans (1980) were based on weekly to monthly water level measurements our data were recorded with hourly to daily intervals. This should not affect the overall shape of the curves however. In our dataset sigmoid curves were most pronounced in fens. This is attributed to natural drainage caused by a slightly sloping terrain rather than artificial drainage of the areas.

Water level time series were also studied by a non-statistical approach, and it was found that four different fluctuation patterns could be recognised (Fig. 5). These different fluctuation patterns are not necessarily differentiated by the *residence time curves* above.

1) The water table is equal to terrain level most of the year with minor draw down events during the summer period. Flooding or stagnating water never occurs because water can

run off at the surface. Typical for natural fens with a substantial groundwater input which is rarely exceed by evapotranspiration

2) No clear maximum water level is observed. This is the case if the water table rarely reaches the ground surface or if surface runoff is not possible. Such pattern is observed for both meadows, bogs, fens and forest wetlands. These patterns are expected to reflect a limited groundwater inflow
3) The water table is mostly equal to terrain in the winter period, but periodic flooding occurs. Typical for fens or meadows located near a river with a limited or unstable groundwater inflow.
4) Fluctuations mainly take place on an annual time scale while the short term response to precipitation and evapotranspiration is limited. This pattern can occur if the soil is porous and highly conductive and hence the water table follow the groundwater level or the water level in an adjacent river or lake. This is the less commonly observed pattern in the dataset and mainly associated with meadows.

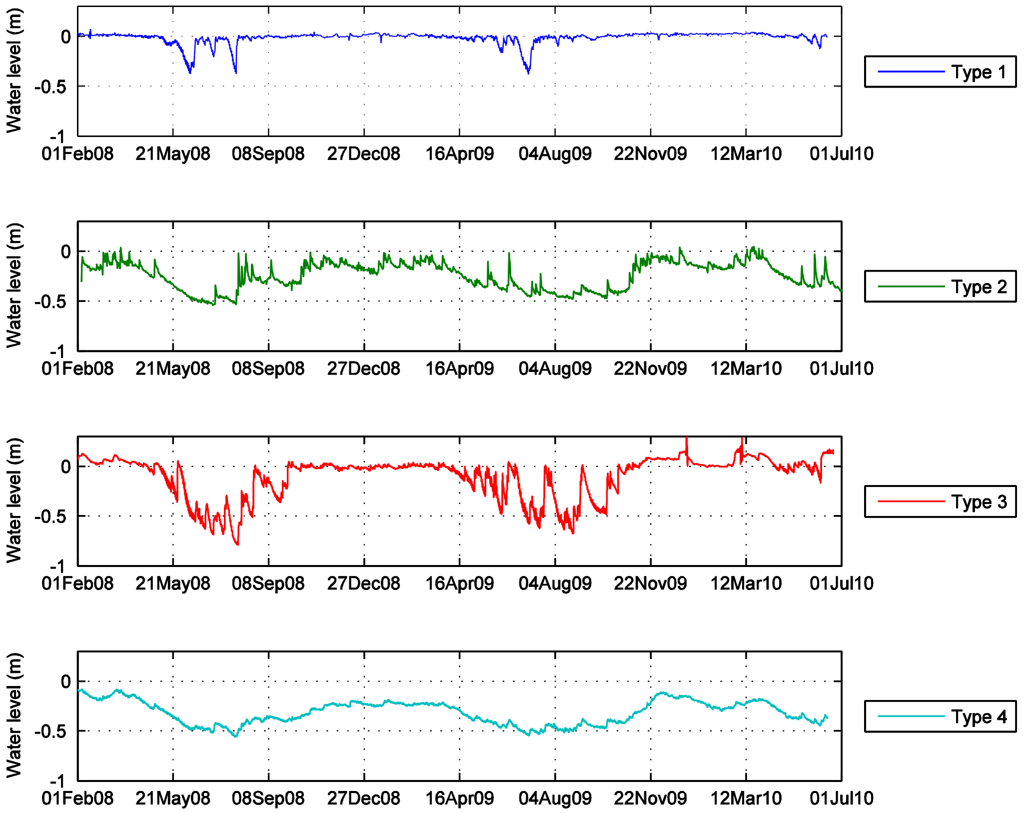

Fig. 5 Observed patterns in water level time series in Danish wetland ecosystems

The ecological relevance of such categorisation based on temporal water table patterns has not been studied at this point. As will be treated in the following section, ecologically relevant statistical measures from water level time series were identified as presented in *Paper III*. Improvement of these correlations might be obtained by grouping the time series in appropriate sub-categories. However, the amount of water level data in Danish GWDTEs is most likely insufficient for this. A similar approach has been used in river ecology to access linkages between flow variations and river ecology (Poff and Ward 1989).

Water level and vegetation

In *Paper I* three water level time series in fens were analysed to identify measures that would reflect the observed gradient in seepage dependent plant species. The water level analyses showed that the three plots differed greatly in the number of days pr. year where the water level depth exceeded 10 cm. However a certain threshold depth of e.g. 10 cm may not be useful to compare fens on a broader scale because of differences in soil types and problems of defining the terrain level due to micro-topography.

In *Paper III* relations between the water level regime and occurrence of fen species and bryophytes were established on a larger dataset. This work was successful in the way that significant direct relations between the water level regime and the measures characterising overall habitat quality were obtained. Compared to previous studies on water level vegetation relations e.g. (Ertsen et al. 1998, Runhaar et al. 1997) focus was on a rather narrow ecological gradient (included only fen habitats), and in this perspective the correlations are convincing.

The overall diversity defined as the total number of species within a given plot showed very poor and insignificant correlations with all water level measures. This may be because the highest overall diversity is found in areas where both wet and dry nutrient poor conditions are found side by side, and therefore species characteristic for dryer environments are registered in the plot. Hence the total number of species is not a good measure with respect to the hydrological functioning in fens. On contrary the number of typical fen species was significantly correlated to the water level variability expressed by *IQR*, while the total number of bryophytes was found to be even closer related to the water level variation. This indicates that the number of typical fen species is a highly relevant measure for management applications, because it defines the overall quality of a fen habitat. We also worked with the occurrence of bryophytes as a measure of habitat quality in fens. Bryophytes are more directly dependent on stable water table conditions and based on the results a promising indicator of both water quantity and quality. It was attempted to address the occurrence of bryophytes which are listed as characteristic to fens, but the analyses showed that the low occurrence hindered successful modelling. Hence it is difficult to obtain statistically significant correlations for typical bryophytes from the dataset. As discussed previously the rarity of species is a fundamental problem when working with species diversity and statistical approaches.

Interesting results were also obtained which indicate possible improvements of eco-hydrological models based on Ellenberg indicators (Ellenberg 1991). The Ellenberg moisture score was significantly correlated to all water level measures but with a large degree of scatter, which is in accordance with Wamelink et al. (2002). But rather surprisingly Ellenberg F was by far closest related to the short term variability (dynamics mainly caused by precipitation and evapotranspiration). In addition the ratio Ellenberg N divided by Ellenberg F (EN/EF) was much closer correlated to the inner quartile range of the water level and at the same time closely related to the bryophyte diversity. This suggests using Ellenberg N divided by Ellenberg F as a surrogate for water level data where these do not exist, rather than just using Ellenberg F.

The analysis did not confirm the general perception in Dutch eco-hydrological studies e.g. (Ertsen et al. 1998, Wamelink et al. 2002) that the spring period (main growing season) is most important for vegetation composition. The results indicate that time series statistics including all seasons show higher correlations with the number of characteristic fen species. When used in modelling in combination with the *nutrient ratio* (Ellenberg N/R), water level in the warmest months (July and August in Denmark) had a slightly higher explanatory power than annual average conditions. In fens with undisturbed hydrology and large groundwater seepage rates it is postulated, that the water level is equal to the terrain at least until 1 May for Danish conditions (Fig. 5 type 1) and that differences between sites are most pronounced during the summer period.

Models for predicting the number of typical species and bryophytes in fens were established by combining water level measures and the nutrient ratio as explanatory variables in *Paper III*. While the *nutrient ratio* has been demonstrated to have a large explanatory power towards the occurrence of typical species (Andersen and Ejrnæs submitted 2011) the inclusion of water level measurements have improved the link to hydrological conditions significantly. In *Paper IV* the vegetative impacts of a change in water level due to groundwater abstraction are discussed. There are large uncertainties involved in using a model based on spatial variability in prediction of temporal changes. Some of the observed variability in water level regime could be caused by plant communities located on different soil types and hence not sharing the same water level preferences. While a clayey soil can be close to saturation high above the water table due to capillary rise, drought might occur in a sandy soil under the same water level conditions. Another important aspect is the temporary mineralisation of nutrients following a lowering of the water table which is not taken into account. The models proposed in *Paper III* should be considered as an estimate of the number of species supported by a new equilibrium in the habitat. If a massive eutrophication is induced shortly after lowering the water table the protected species can disappear long time before a new supporting equilibrium is established.

A maximum of 2-3 cm during critical periods (7 mm as a yearly average) is not a dramatic change in water level for the area considered in *Paper IV*. Referring to the established statistical relations between water level and typical fen species in Denmark, the water levels at the site are very stable and near the terrain, even if altered by 3 cm. Moreover it is well known, that peat in fens which are affected by substantial groundwater seepage has an almost “floating” character. Several authors have documented changes in peat surface levels caused by changes in water storage (Ingram 1983, Price 2003, Roulet 1991, Strack et al. 2006, Wassen and Joosten 1996). Roulet (1991) even showed that changes in peat surface level of several centimetres a day took place during the summer period of a subarctic fen in Canada. A change in the order of 2-3 centimetres is unlikely to pose a significant affect to the vegetation in fens because 1) the peat surface can compensate some of the effect by adapting to a lower pressure from groundwater, 2) The change is small compared to natural variations, 3) the upwards hydraulic gradient will still be intact all year around and therefore the hydrological functioning is intact.

Water-level vegetation relations were studied using vegetation measures which reflect the overall status in fen habitats (*Paper III*). However, the dataset also contained some useful information on individual species, which will briefly be presented here. 35 sites were investigated and in the following analyses the dataset was divided into two groups. The "wet" group contains 17 sites where the annual mean water table depth is from 2 to 13 cm. The "dry" group contains 18 sites where the mean water table depth is from 13 to 35 cm. For each of the typical fen species I then found the occurrence in wet and dry sites respectively (Fig. 6).

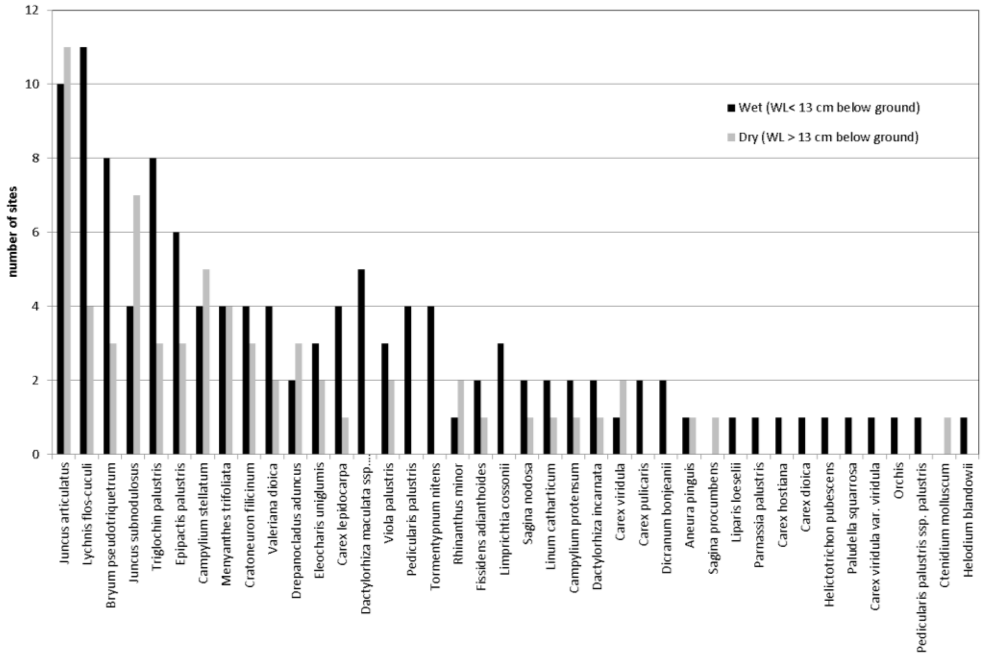

Fig. 6. Occurrences of each typical fen species in the "wettest" and "driest" group of the plots studied. A large difference in occurrences between wet and dry plot indicate a strong preference and hence a suitable wetness indicator.

A handful of species show fairly strong preferences for wet conditions; *Lychnis flos-cuculi* (11 wet / 4 dry), *Triglochin palustris* (8/3), *Bryum pseudotriquetrum* (8/3), *Dachtylorhiza maculata ssp. maculata* (5/0). The Ellenberg moisture score of these five species is in the range from 7-9. In the applied list of typical species *Menyanthes trifoliate* has an Ellenberg moisture score of 10 (highest in the list), but showed no preferences for wet or dry conditions. The 10 most common species on the list were found in both groups, however, slightly more frequent in wet sites. Of the 10 rarest species (only 1 occurrence in the dataset) 8 belong to the "wet" group and 2 were found on drier sites. Little statistical significance can be obtained for individual species from 35 sites however two aspects seem evident; 1) The number of typical species is higher at wet sites, and 2) Rare species occur more frequently on wet sites.

Distributed groundwater modelling

Distributed modelling can be an important tool in order to predict changes in water level and seepage in fen areas, as demonstrated in *Paper IV*. A substantial amount of data was available including results of long term monitoring of natural hydrology and full scale pumping tests that were used in model calibration and validation. Validating the predictive capabilities was not possible on a plot scale, because the disturbance from the pumping could not clearly be distinguished from natural fluctuations in the measurements. During the process of building and calibrating the model it was found that local springs along the edge of the river valley had a large influence on the discharge in the river valley. In *Paper I* springs were estimated to conduct at least twenty times more water than seepage processes supplying the fens and the distance between spring and fen was small. This was a challenge in terms of using distributed modelling because springs are local scale processes that somehow have to be described and resolved in a numerical grid. This combined with the presence of ditches in the river valley lead to the conclusion that a rough regional groundwater model (large grid cells >100m) would not be able to produce reliable results in such a setting. Moreover the model was highly sensitive towards the extent of low-permeable river valley deposits and the water level in the springs. The model was quite capable of reproducing the flow in natural springs during the pumping tests while it had some problems with the natural water level dynamics in the fen. This could possibly be a result of the heterogeneity in the river valley deposits as well as micro topographic variations which are not described in the model. The vertical gradient was fairly well-described and there is good reason to have larger confidence in the predicted relative changes to water level and fluxes compared to prediction of absolute values. An obvious alternative would be to use the 3D model to predict changes in pressure head underneath the river valley and then transfer these predictions to a 1D model e.g. as presented in *Paper II*.

The uncertainties of the predictions were not accessed and the task would have been practically unfeasible due to the large computational demand. On the other hand there are no real alternatives to distributed modelling in stream valleys, where heterogenic discharge patterns are more a rule than an exception. A pragmatic engineering confidence in the model results were obtained through reproduction of numerous observations.

Perspectives and closing remarks

In the foregoing mechanisms involved in hydrological impacts in discharge wetlands have been discussed. The study has focused on tools for prediction of hydrological quantities, which are relevant for seepage dependent plant communities. It has been shown that physically based model approaches are highly valuable in their predictive capability. The numerical tools have long been available and should be more widely used to provide a solid hydrological evaluation and to support decisions regarding groundwater dependent ecosystems. This study provided examples and new techniques for predicting seepage and water level changes on a point scale. However, what is really limiting future assessments of GWDTEs is the linkage between hydrology and vegetation. So far, it was only attempted to correlate water level directly to the occurrence of certain species and such statistical relations have little predictive power, when it comes to changes related to groundwater abstraction. This is because it does not deal with changes in water and soil chemistry followed by a lowering of the water table. Using the statistical relations makes it possible to predict a minimum expected vegetation response, however, there is a need to know the worst case or ideally the most likely change including uncertainty bounds.

A way forward might be to improve the predictions of chemical changes in the soil. In this aspect the proposed method for determining seepage (*Paper II*) has some important perspectives, which have not been discussed so far. Besides being directly correlated to certain plant species and plant communities (Klijn and Witte 1999) seepage is needed for successful modelling of water chemistry in fens (Kemmers et al. 2003). Chemical modelling in peat soils is not simple due to the large number of interacting processes involved; however, the chances of success greatly improve if the dynamic inflows and outflows of precipitation and groundwater can be simulated. The presented model (*Paper II*) combined with the output from a 3D groundwater model could form the basis for chemical modelling by delivering these fluxes and the changes imposed to them by abstraction. Even if modelling all processes controlling nutrient availability and pH proves too complex there might be relevant compromises. Schot et al. (2004) studied the dynamic form of rain water lenses in drained fens in a synthetic setup where groundwater seepage rates were assumed. Applying site specific seepage rates may lead to improved insight in mixing of groundwater and precipitation with implications for pH in the water. Kemmers et al. (2003) demonstrated how chemical equilibrium modelling could be used to study key factors and processes in base regulation of fens given that fluxes and base saturation of groundwater is known.

If chemical variables (soil-water pH and nutrient availability) can be predicted the chance of making accurate predictions of the vegetative response increases. In the Netherlands eco-hydrological models have been developed for fens, meadow and dune slack ecosystems for decades. Empirical statistical models like HYVEG (Noest 1994a) , ITORS (Ertsen et al. 1995) have proven quite reliable if sufficient information on site abiotic conditions (soil composition, water chemistry, water level conditions etc.) can be provided. It is likely that these models cannot be applied in other geographical regions without recalibrating them on local data. It is doubtful whether sufficient data for GWDTEs in Denmark exists. Denmark and Holland are, however, similar in climate conditions and there might at least be similarities in environmental conditions supporting the habitats.

The task ahead therefore narrows down to a matter of making reliable predictions of changes to these chemical input variables resulting from hydrological changes. This may, however, not be as simple as it sounds. In my mind mechanistic models are the most promising way forward. By explicitly considering the processes involved they have the potential to include feedback mechanisms between processes as well as handling different scales of time on which these processes occur (Fujita et al. 2007).

At the field study site in Lindenborg river valley the simulated response to groundwater abstraction was a 2-3 cm lowering of the water table in dry periods. Following precautionary principles of the European directives it can be argued that this is an adverse effect on the ecosystem. An effect in this order of magnitude would not be recognisable from water level measurements but can only be proved by hydrological modelling. Many other groundwater abstractions exist in the catchment to Lindenborg River. Due to the distance to the fen their effect is much smaller – perhaps in the order of mm rather than cm at this site. This study did not support meaningful thresholds below which there are no risks involved in abstraction near GWDTEs. This is partly because water level preferences for vegetation communities are not independent of other environmental conditions.

However, most experts would definitely agree that water level changes in the order of mm cannot be significant when daily (natural) fluctuations are as high as 10 cm. Unless scientists are able to greatly improve predictions of water and soil chemistry in wetlands there will be a continued scientific gap, where the sound judgement of experts in hydrology and ecology is necessary. In this aspect this study point towards a *key parameter* controlling the hydrological functioning of these ecosystem, which is *the hydraulic gradient* between the adjacent groundwater aquifer and the wetland. In stable seepage areas this hydraulic gradient is directed upwards all year around while in other areas the gradient is periodically reversed as a part of the annual cycle. Any hydrological impact which is shown to dramatically alter the magnitude or direction of this gradient will pose a threat to the integrity of groundwater dependent terrestrial ecosystems.

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Part 2 Appendices

APPENDIX I

HYDROLOGICAL MODELLING OF SMALL SCALE PROCESSES IN A WETLAND HABITAT

Presented at the 2nd International Multidisciplinary Conference on Hydrology and Ecology: Ecosystems Interfacing with Groundwater and Surface water, 20-23 April 2009, Vienna Austria
Editors: Jiri Bruthans, Karel Kovar and Peter Nachtnebel

Hydrological modelling of small scale processes in a wetland habitat

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Summary

Numerical modelling of the hydrology in a Danish rich fen area has been conducted. By collecting various data in the field the model has been successfully calibrated and the flow paths as well as the groundwater discharge distribution have been simulated in details. The results of this work have shown that distributed numerical models can be applied to local scale problems and that natural springs, ditches, the geological conditions as well as the local topographic variations have a significant influence on the flow paths in the examined rich fen area.

1 INTRODUCTION AND BACKGROUND

The interaction between groundwater and surface water in riparian areas is of great significance for the whole aquatic environment and for the groundwater dependent terrestrial ecosystems. Meeting the standards of the EU Water Framework Directive requires an improved knowledge on site specific hydrological processes which affect the preservation status of the ecosystem.

Groundwater modelling is widely used as a tool for evaluating the groundwater resources on a regional scale and thus a great effort has been put into collecting a sufficient amount of data at this scale for model construction, calibration and validation. However, when it comes to describing the hydrological processes, which occur on field and point scale, the data resolution is often insufficient (Beven 2008). Water level, water discharge, water chemistry, and nutrients availability are all significant elements affecting plant communities in wetland habitats (Van Diggelen et al. 2006). A key to predicting each of these elements lies in an improvement of the methods for modelling the detailed flow processes.

2 MATERIALS AND METHODS

Study site

The site is located in the northern part of Denmark in the Lindenborg River valley and the adjacent aquifer consists of fractured high yield limestone formations. In the river valley a peat layer of approximately 1-2 m and below that an organic silt layer of 1-7 m were found. The area that was intensively studied is illustrated in Fig. 7.

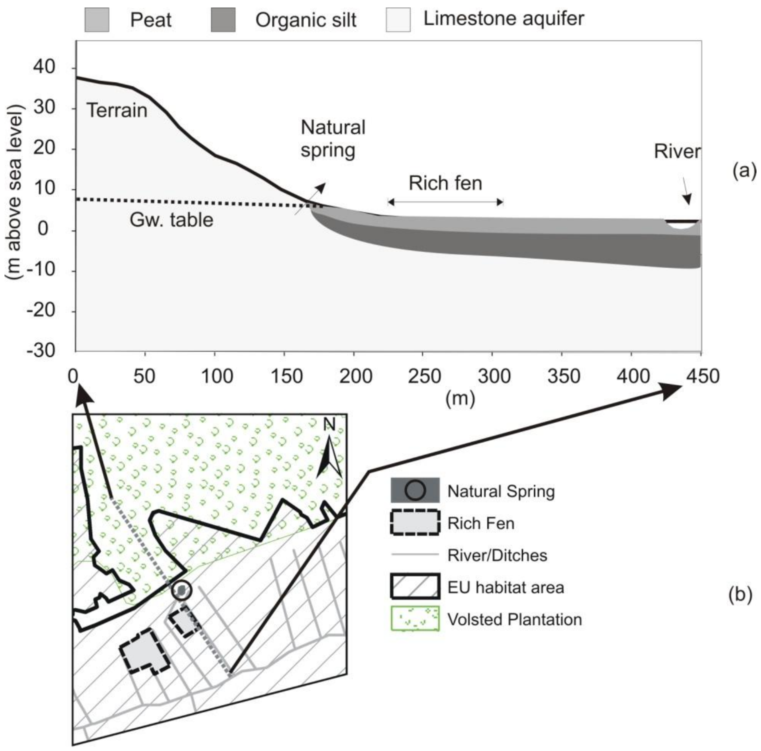

Fig. 7. Illustration of the study site. (a) Profile view of the river valley showing the location of the spring and the rich fen. (b) Map of the study site and the location of the profile in (a).

Data collection and numerical hydrological model

Continuous water level measurements were conducted in 9 wells in the river valley (6 piezometers 5-7 metres below the surface and 3 short water level wells) and in a deep monitoring well in the plantation. The water level was stored every 2 hours from March 2007 to present by use of pressure loggers (mini-diver from Schlumberger Water Services).

Discharge was measured in springs and ditches in the valley using a 50 mm propeller. In the ditches the flow rates were small (<2 L s^{-1}) and it was necessary to use a plate to cut off the ditches and only allow the water to run through an 80 mm hole. Such device was constructed and calibrated in a laboratory before taken into the field.

A 3D numerical model that covers an area of 0.5 km^2 corresponding to Fig. 7b has been constructed using the Mike She code (Abbott et al. 1986). The boundary conditions used were extracted from a regional model, which was validated against both water level and discharge measurements in the catchment area. In order to describe the small scale hydrological processes in the springs and ditches surrounding the rich fen area a horizontal resolution of 5 x 5 metres was chosen.

3 RESULTS

Fig. 8 presents water level data from the plantation and from the rich fen, and at each location two filter depths are monitored.

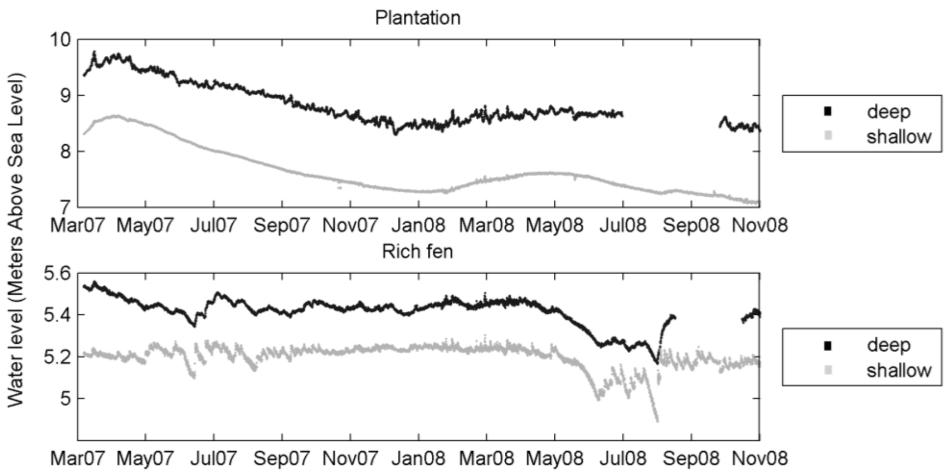

Fig. 8. Water levels measured in the plantation and in the rich fen. The horizontal distance between the plantation and the rich fen is 1km. The deep filters are in both cases positioned below a semi-confining layer and the upper filters measure the water table.

From the water level measurements it is clear that there is an upward pressure gradient in the area and that this gradient is fairly constant the entire period from May 2007 until November 2008. This applies to both the plantation and the rich fen area. The amount of water discharged to the fen area is proportional to the magnitude of this pressure gradient. In the plantation, the maximum water level in the spring of 2007 was approximately 1 m higher than in the spring of 2008. In the fen area the same tendency is seen to some extent in the deep filter, but not in the surface water level, which is controlled by the ditches and the terrain level.

The discharge of groundwater to the surface was measured in ditches and natural springs in the study area (Fig. 7b). The results are compared to simulated discharge rates in table 1. The springs account for more than 90% of the discharge to the surface. The measured discharge through the rich fen is estimated by the measuring discharge in the surrounding ditches.

Table 1 Discharge rates measured in natural springs and ditches compared to model results. The simulated discharge rates do not include evapotranspiration.

	Measured discharge	Simulated discharge
Natural springs	25 ($L\ s^{-1}$)	23 ($L\ s^{-1}$)
Ditches (sum of 10)	3 ($L\ s^{-1}$)	3.2 ($L\ s^{-1}$)
Rich fen area (sum of 2)	< 0.2 ($L\ s^{-1}$)	0.07 ($L\ s^{-1}$) = 1.2 (mm/day)

Fig. 9 illustrates the simulated flow patterns. In the left (a) flow vectors in the surface layer (peat) of the rich fen indicate the effect of the ditches. The profile view (b) illustrates how conditions on the surface affect flow paths in the underlying aquifer.

(a) surface layer (b) profile view

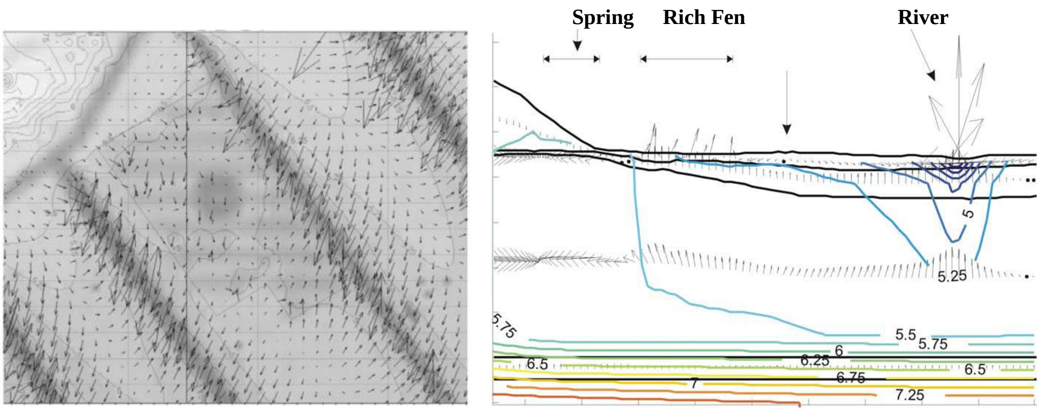

Fig. 9. Simulated flow vectors in the rich fen area. (a) Flow vectors in the surface layer (peat). (b) A profile view through all layers of the model. The position of the profile is similar to the profile in Fig. 7 .

4 DISCUSSION AND CONCLUSION

The water level measurements provide valuable information in relation to calibration of the model as well as knowledge on the hydrological system in general. Monitoring the vertical pressure gradient gives an indirect measure of the discharge variations and improves knowledge on the dynamics of areas fed by groundwater significantly. Quantifying the discharge rate in springs and ditches by direct measurements is possible for flow rates >0.2 $L\ s^{-1}$ with the applied method.

By using a regional hydrological model to provide the boundary conditions and local measurements of water levels and discharge rates to provide the primary calibration and validation data it was possible to simulate small scale hydrology in a Danish rich fen. The average groundwater flow through the rich fen was found by simulation to be 1.2 mm/day.

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APPENDIX II

HYDROLOGISKE OG VANDKEMISKE FORUDSÆTNINGER FOR EN GOD NATURTILSTAND I GRUNDVANDSAFHÆNGIGE TERRESTRISKE ØKOSYSTEMER

English title: Hydrological and chemical requirements for favourable conservation status in groundwater dependent terrestrial ecosystems

The original document can be downloaded from:
http://vbn.aau.dk/files/42683139/Hydrologiske_og_vandkemiske_foruds_tninger_for_en_god_naturtilstand_i_grundvandsafh_ngige_terrestriske_kosystemer.pdf

English summary *(translation of Danish summary in the document)*

The document is a result of bringing together Danish hydrologists, terrestrial ecologists, freshwater biologists and experts on groundwater in the study of groundwater dependent ecosystems. The aim of the project was to investigate un-described links between different sub-programmes of the national Danish monitoring programme (NOVANA) dealing with groundwater, surface water and terrestrial ecosystems. Moreover a supplementary data collection aimed at investigating the hydrological and chemical conditions supporting these habitats. On this basis the project provides recommendations for the coming revision of the NOVANA programme. The project has focused on alkaline fens, defined as nutrient limited but diverse terrestrial vegetation dominated by bryophytes, sedges and herbs. The fen habitats require alkaline, nutrient-poor groundwater and depend to some extend on management in terms of light grazing or mowing. Fens in Denmark are extremely limited in their extent as a result of de-watering, eutrophication and changed grazing practices; however, they host several rare plant species and invertebrates. Analysing existing data from the sub-programmes has led to: 1) Development of models for classification and assessment of fens based on their vegetation. These models are well-suited for fast and cost-efficient screening of large datasets, selection of sites for further monitoring and assessment of sites for status and vulnerability. 2) Demonstration of the vulnerability of fens towards groundwater abstraction in the catchment through GIS analyses and model results from the national groundwater model (DK-model) compared to quality of fens on Zealand. 3) Demonstration of the dependency of a constant groundwater supply supporting a constant water level most of the year. Moreover the supplementary data collection has shown: 1) A significant relation between vegetation and inorganic nitrogen and phosphorus. 2) Large variability in nutrients with depth and season. 3) The best fens exist for nitrate concentrations below 1.3 mg NO_3^-/l.

NOTAT

Modtagere:

Styringsgrupperne for fagdatacentrene for grundvand, ferskvand og biodiversitet
By og Landskabsstyrelsen, Miljøovervågningssekretariatet

Forfattere: Rasmus Ejrnæs[1], Dagmar Kappel Andersen[1], Anette Battrup-Pedersen[1], Christian Damgaard[1], Bettine Nygaard[1], John Bøhme Dybkjær[1], Britt Stenhøj Christensen[2], Bertel Nilsson[2], Ole Munch Johansen[3]
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Angående: hydrologi, vandkemi og naturtilstand i de grundvandsafhængige terrestriske økosystemer

DANMARKS MILJØUNDERSØGELSER
AARHUS UNIVERSITET

Hydrologiske og vandkemiske forudsætninger for en god naturtilstand i grundvandsafhængige terrestriske økosystemer.

Forord

Nærværende notat beskriver resultaterne af et tværgående NOVANA-projekt. Først beskrives projektets faglige baggrund og formål. Dernæst beskrives og diskuteres resultaterne og endelig gennemgås projektets anbefalinger til det reviderede overvågningsprogram.

Baggrund

Danmark har, i medfør af flere EU-direktiver, forpligtet sig til at sikre opretholdelse af en god tilstand af de grundvandsafhængige terrestriske økosystemer. Habitatdirektivet fra 1992 omfatter en række navngivne habitattyper som forekommer på fugtig eller våd bund, herunder flere typer som indirekte eller direkte er påvirket af grundvand. Formålet med direktivet er at opnå gunstig bevaringsstatus og hydrologi og vandkemi har stor betydning for disse typers bevaringsstatus. Vandrammedirektivet fra 2000 målsætter, beskytter og forvalter vandøkosystemer, men også terrestriske økosystemer som er afhængige af disse. Eksempelvis defineres den tilgængelige grundvandsressource (for udnyttelse) i direktivet som den vandressource som kan udnyttes "uden væsentlig skadelig indvirkning på tilknyttede terrestriske økosystemer". Endelig er der grundvandsdirektivet fra 2006 som tager sigte på at beskytte grundvandsressourcen mod forurening med henblik på drikkevandskvaliteten og de grundvandsafhængige økosystemer (herunder de terrestriske). I direktivets bilag er fastsat grænseværdier for nitrat og pesticider, men det er også nævnt at der kan fastsættes strengere grænser hvis det er nødvendigt for at undgå væsentlig beskadigelse af terrestriske økosystemer, som er direkte afhængige af grundvandsforekomsten. Set i dette lys er der stort behov for at få et overblik over hvilke terrestriske naturtyper som er afhængige af grundvand og disse naturtypers følsomhed over for ændringer i mængden og kvaliteten af de grundvandsforekomster som de er knyttet til.

Tabel 1. Mosetyper som er eller kan være afhængige af grundvand. Indirekte afhængighed hentyder til den potentielle betydning af en høj grundvandsstand under en i øvrigt regnvandsbetinget højmose.

Naturtype	Undertype	Grundvandsafhængighed
Klitlavning (2190)	Kalkrig undertype	Direkte
Tidvis våd eng (6410)	Kalkrig undertype	Direkte
Højmose (7110)		Indirekte
Hængesæk (7140)	Kalkrig undertype	Direkte
Hvas avneknippemose (7210)		Direkte
Kildevæld (7220)		Direkte
Rigkær (7230)		Direkte
Elle- og askeskov (91E0)		Direkte
Rørsump (§3)	Åben type	Direkte
Våd eng (§3)	Kalkrig undertype	Direkte

Tabel 1 viser hvilke terrestriske naturtyper som formodes at være afhængige af grundvand, enten direkte eller indirekte. Ved direkte forstås at naturtypen kun forekommer hvor det kalkrige, mineralrige og næringsfattige grundvand vælder frem eller trykkes ud/op i rodzonen. Dette gælder for rigkær (7230), kalkrigt kildevæld (7220) og hvas avneknippemose (7210). For nogle naturtyper gælder at visse undertyper både kan forekomme i en regnvandsbetinget undertype med lav pH og en grundvandsbetinget undertype ved høj pH. Dette gælder for tidvis våd eng (6410), hængesæk (7140) og fugtige klitlavninger (2190), hvor de kalkrige undertyper er direkte grundvandsbetinget. Endelig kan naturtyper som ikke påvirkes direkte af grundvandet, være afhængige af et højt grundvandsspejl, hvor en sænkning af grundvandsspejlet kan føre til ødelæggelse af forekomsten. Dette gælder for højmoser (7110), hvor selve vegetationslaget alene modtager regnvand (ombrotrofe). Selvom højmoser og rigkær findes i hver sin ende af en hydrologisk og vandkemisk gradient, har palæoøkologiske studier vist at forandringer i det hydrologiske system eller i vandets strømningsveje kan føre til at højmoser udvikles spontant oven på gamle rigkær, eller rigkær udvikles inde i højmoser. Forandringen i naturtypen opstår hvis et udstrømningsområde som følge af ændret grundvandstryk eller hydraulisk ledningsevne pludselig ændrer sig til at blive et infiltrationsområde præget af regnvandets kemi, eller omvendt, at grundvandets strømningsveje fører til udstrømning i et område som før var ombrotroft. På trods af disse eksempler er rigkær ofte meget stabile og kan bestå i tusinder af år så længe de hydrologiske forudsætninger er til stede (Janssen 1972).

Vi har i dette projekt valgt at fokusere på rigkær fordi grundvandsafhængigheden er veldokumenteret og fordi de repræsenterer de relevante problemstillinger for kildevæld, hvas avneknippemose, fugtige klitlavninger, tidvis våd eng og hængesæk. Vi har dog også inddraget kildevæld i enkelte analyser fordi NOVANA-overvågningen af kildevæld har omfattet målinger af nitrat i vand fra naturtypen. I praksis vil der udvikles rigkærsvegetation omkring kildevæld med mindre grundvandet er næringsforurenet.

Hydrologiske forudsætninger for rigkær

Mens højmoser og fattigkær har været den fremherskende mosetype i den boreale zone, har rigkær oprindeligt været blandt de dominerende mosetyper i den tempererede zone (Joosten & Clarke 2002, Grootjans et al. 2006). Rigkærsområder har været interessante områder at dræne og udnytte til dyrkning og omlægning med kulturgræsser. Desuden har grundvandsressourcen som skaber rigkær været under pres gennem dræning af infiltrationsområder, vandindvinding til drikkevand, markvanding og dambrug, og rigkær er i dag en sjælden naturtype. Rigkær kan findes i tilknytning til meget forskellige hydrologiske systemer, men vandstand, vandstandsfluktuationer, pH, basemætning og næringsstofindhold er overraskende ens de steder hvor rigkær findes (Grootjans et al. 2006). Således kan man finde rigkær i klitlavninger på sandet jord, i ådale på tørvejord og på bakkeskråninger hvor grundvandet trykkes frem. Fælles for rigkær er at de dannes på steder med gennemstrømmende grundvand, hvor geokemiske processer modvirker forsuring og reducerer tilgængeligheden af næringsstoffer i rodzonen. Grundvandets altafgørende rolle for dannelsen af rigkær kan også forklare hvorfor man af og til kan finde kalkelskende artsrig rigkærsvegetation omgivet af store strækninger med artsfattig kalkskyende hede- og mosevegetation. Karakteristisk for rigkær er endvidere en vandstand som udviser meget små fluktuationer sammenlignet med mosetyper som er afhængige af overfladevand eller regnvand. Ofte vil der være et lille, men mærkbart, fald i vandstanden i sommermånederne. Ofte vil den vandmættede zone ligge stabilt indenfor 10 cm fra overfladen af tørven (Boomer & Bedford 2008a).

Vandkemiske forudsætninger for rigkær

Den stadige tilførsel af køligt, kalkrigt, iltfattigt og næringsfattigt grundvand er den afgørende forudsætning for rigkærets planter og dyr. Vandets høje indhold af calciumkarbonat modvirker forsuring og stabiliserer pH mellem 5,5 og 8 afhængig af balancen mellem regnvand og grundvand i rigkæret samt af grundvandets kalkindhold. Det iltfattige grundvand har et lavt indhold af plantetilgængeligt kvælstof og fosfor, men en høj basemætning baseret på indhold af magnesium, jern og kalk. Fosforbegrænsning synes at være et gennemgående træk for rigkær, og i særdeleshed for lokaliteter med truede plantearter (Wassen et al. 2005). Indholdet af calciumkarbonat og jern-ioner medvirker til at binde fosfor så det gøres utilgængeligt for planterne og her spiller jern tilsyneladende den største rolle (Boomer & Bedford 2008b, van der Welle et al. 2008). De iltfattige forhold i rodzonen medvirker til at mineraliseringen hæmmes. Resultatet bliver et lavproduktivt og artsrigt plantesamfund bestående af lave urter og mosser, med en langsom opbygning af et tørvelag.

Antropogene påvirkninger af hydrologi og vandkemi

Både hydrologi og vandkemi har været og er stadigvæk under stærk antropogen påvirkning. Hele det hydrologiske kredsløb er stærkt modificeret ved dræning som afleder vandet overfladisk gennem dræn og grøfter i stedet for at lade det infiltrere til de dybe grundvandsmagasiner hvor det ville blive reduceret, afkølet og mættet med kalk, magnesium og jern og strømme ud af vældzonerne i ådale og kyster. Dette påvirker selvsagt mængden af grundvand i vældzonerne, men i høj grad også kvaliteten af vandet i de terrestriske vådområder, hvor næringsbelastet drænvand og overfladevand mange steder er den dominerende vandressource, hvilket fører til udviklingen af monotone højstaudesamfund af næringselskende flerårige græsser og høje bredbladede urter. Dertil kommer at udnyttelsen af ådalene til landbrug og dambrug også har medført en direkte dræning i ådalene, så også det fremvældende grundvand ledes væk i stedet for at sive frem til vandløb, sø eller hav gennem den vandmættede tørv.

Udtørring

Den udtørring som finder sted hvis grundvandstrykket falder i et rigkær vil forandre vegetationen fra en våd mose med udbredt forekomst af mosser og specialiserede moseplanter til en mere eng-agtig vegetation, der er så tør at den kan bruges til græsning eller høslæt i sommerhalvåret. Selvom grundvandstrykket sænkes, kan vegetationen imidlertid godt vedblive at være artsrig, hvis afvandingen ikke har medført en samtidig eutrofiering (Grootjans et al. 2006). I bedste fald kan der udvikles kalkrige tidvist våde enge; artsrige, men uden en række af rigkærets typiske mos-arter, som ikke tåler udtørring (Mälson et al. 2007). Udtørringen indebærer dog også en risiko for forsuring og eutrofiering. Udtørringen kan føre til en iltning og mineralisering af tørven, hvilket leder til en frigivelse af næringsstoffer. En sådan frigivelse af næringsstoffer som allerede findes i tørven, men utilgængeligt for planterne, kaldes "intern eutrofiering" (Lamers et al. 2006). Risikoen for dette er stor hvis økosystemet har fået tilført næringsstoffer med grundvand eller overfladevand, som har været immobiliseret i den iltfrie vandmættede tørv (Lamers et al. 2006). Afvanding kan også medføre en forøget indblanding af udefrakommende næringsbelastet overfladevand i kærområdet, hvis området ændres fra udstrømningsområde til infiltrationsområde for overfladevand. Eutrofiering forårsaget af ude fra kommende næringsstoffer kaldes "ekstern eutrofiering", og næringsstofferne kan her komme fra eksempelvis direkte gødskning, markdræn eller vandløbsoversvømmelse. Endelig kan en vandtrykssænkning i rigkæret medføre en forsuring, når balancen mellem kalkrigt grundvand og regnvand forskydes. Dette kan medføre øget vækst af tørvemosser som i sig selv kan forsure miljøet yderligere og fortrænge den karakteristiske rigkærsmosflora (Mälson et al. 2006, Kooijmann & Paulissen 2006).

Ændring af vandkemi

Menneskets arealudnyttelse har forandret den kemiske sammensætning af både regnvand, overfladevand og grundvand. Regnvandet indeholder stærkt forøgede kvælstofmængder, overfladevandet indeholder stærkt forøgede mængder af sulfat, nitrat/ammonium og fosfat og grundvandet indeholder forhøjede niveauer af nitrat. Endvidere er der fundet pesticidrester i grundvand og overfladevand, ja selv i regnvand (Lewan et al, 2009). Tilførsel af kvælstof og fosfor med vandet medfører ekstern eutrofiering i rigkær. Kvælstof vil under de rette betingelser kunne denitrificeres i den anaerobe vandmættede tørv og fosfor vil kunne immobiliseres ved binding til jern eller calcium. Sulfatbelastning kan medføre forsuring, en frigivelse af jernbundet fosfor samt en omdannelse til fyto-toxisk sulfid (van der Welle et al. 2008). De kemiske processer i tørven er imidlertid uhyre komplicerede, og effekterne af en tilførsel af kvælstof, fosfor eller sulfat afhænger af de hydrologiske og vandkemiske forhold i vældområdet og kan være vanskelige at forudsige. Eksempelvis kan reduktionen af tilført nitrat medføre en oxidation af jernsulfid og frigivelse af sulfat og plantetilgængeligt fosfor i kraft af de interne omdannelser i tørven (Lamers et al. 2006, van der Welle et al. 2008). I sulfatrige tørvejorde i landbrugsintensive områder, kan nitratforurening og denitrifikation være den væsentligste kilde til sulfatdannelse og efterfølgende intern eutrofiering ved frigivelse af jernbundet fosfor (van der Welle et al. 2008, Boomer & Bedford 2008b). Den interne eutrofiering vil forøges ved pH-fald som følge af nedsat udstrømning af grundvand (Boomer & Bedford 2008b).

Andre væsentlige påvirkninger af rigkær

De mest artsrige rigkær er lysåbne og i mange tilfælde kræves der en tilbagevendende forstyrrelse i form af græsning eller høslæt for at forhindre en tilgroning med vedplanter som pil eller el der tåler en høj vandstand og vandbevægelse. Ved stærk udstrømning af grundvand kan rigkær være naturligt lysåbne, men mange områder er i dag hydrologisk modificerede eller påvirkede af næringsstoffer i en grad hvor græsning eller høslæt er en forudsætning for deres opretholdelse. Græsning og høslæt medvirker også til at holde potentielt dominerende konkurrenceplanter i skak, og således kan et artsrigt rigkær hvor græsningen ophører med tiden udvikle sig til rørsump med tagrør eller hvas avneknippe eller et samfund af høje bredbladede urter. Hvis området har en naturlig hydrologi og vandkemi, vil det dog typisk være så næringsfattigt at de høje urter aldrig opnår fuld dominans. Græsning opfattes som en del af de naturlige forudsætninger for rigkær, ligesom en naturlig hydrologi og vandkemi, men græsningen i landskabet er ligesom de øvrige forudsætninger stærkt antropogent påvirket i kraft af udryddelsen af de naturlige græsædere og den faldende efterspørgsel efter naturområder som foderressource i det moderne landbrug.

Tærskelværdier for hydrologi og vandkemi

Alle tre EU-direktiver lægger op til udviklingen af kriterier eller grænseværdier for de grundvandsafhængige terrestriske økosystemer. Habitatdirektivet i form af kriterier for gunstig bevaringsstatus (struktur og funktion samt indikatorarter) og vanddirektiverne i form af grænseværdier for en god økologisk tilstand. Hvad hydrologi og vandkemi angår, er det oplagt at fokusere på mængden af grundvand i rigkærsforekomsterne, opblandingen af grundvand med overfladevand samt vandets indhold af næringssalte og miljøfremmede stoffer.

Det nærmeste vi er kommet danske kriterier for hydrologi og vandkemi er rapporten om kriterier for gunstig bevaringsstatus (Søgaard et al. 2003), som sætter som kriterium at indholdet af nitrat-N skal være indenfor den forventede variationsbredde for naturtypen i Danmark og desuden stabilt eller i bedring. Et niveau på under 0.03 mg N/liter vand er foreslået.

Dette kriterium underbygges dog ikke af data indsamlet i NOVANA for kildevæld og hængesæk, som især for de grundvandsbetingede kildevæld udviser væsentligt højere værdier, selv for kildevæld i en god naturtilstand. Data viser godt nok en signifikant negativ sammenhæng mellem nitratindholdet i vandet og den biologiske tilstand, men underbygger ikke et fast kriterium, eftersom sammenhængen ikke er entydig (Goldberg et al. 2008). Et af de iboende problemer ved NOVANA-data fra kildevæld er dog at nitratmålingerne udelukkende er foretaget i sommerperioden, hvilket er utilstrækkeligt til at belyse effekter af tilførsel af overfladevand i forbindelse med udvaskningshændelser i oplandet. På trods af stor variation i de målte koncentrationer af nitrat i kildevæld, tyder NOVANA-data dog på at 0,03 mg/l NO3-N er et urealistisk lavt kriterium og at den gode tilstand snarere findes ved nitrat-N indhold på <1-3 mg/l.

VVM, naturplaner og vandplaner

Som led i implementeringen af EU's direktiver skal der gennemføres en beskyttelse og målrettet forvaltning af såvel grundvandsressourcen som de grundvandsafhængige økosystemer. Dette vil bl.a. foregå ved udarbejdelse af vand- og naturplaner, konkrete indsatsplaner og VVM-vurderinger af miljøeffekter ved vandindvinding. For at kunne implementere direktiverne er det derfor nødvendigt at bygge på en fagligt velunderbygget forståelse af økosystemernes afhængighed af hydrologi og vandkemi og af effekterne på antropogene påvirkninger af grundvandsressourcen.

Projektets formål

På denne baggrund besluttedes det at gennemføre et tværgående økohydrologiprojekt mellem relevante aktører i NOVANA. Projektgruppen inkluderede DMU-afdelinger med ansvar for delprogrammer for overvågning af natur og overfladevand samt GEUS med ansvar for overvågning af grundvand.

Projektets formål var følgende:

- at undersøge og beskrive hvordan data fra grundvandsovervågning, herunder regionale og lokale modeller for det hydrologiske kredsløb, kan anvendes som forklaringsvariabler for tilstanden og udviklingen af naturtilstanden i højmoser, lavmoser og kilder omfattet af Habitatdirektivet.
- at undersøge og beskrive hvordan indsamlingen af data i de tre omfattede NOVANA-delprogrammer kan optimeres med henblik på at opnå størst mulig synergi i beskrivelsen af det hydrologiske kredsløb og dets betydning for tilstand og udvikling af Habitatdirektivets naturtyper.

I projektet blev der som beskrevet ovenfor sat særlig fokus på rigkær som en sårbar og repræsentativ naturtyper for beskrivelsen af de hydrologiske og vandkemiske forudsætninger for grundvandsafhængige terrestriske økosystemer. Det blev tidligt klart at der ikke i de eksisterende NOVANA-data findes sammenhørende detaljerede hydrologiske målinger eller modeller og detaljerede målinger af naturtilstand i tilknyttede rigkær og kildevæld, og vi har derfor ikke haft mulighed for at koble natur og grundvandsmodellering på lokal skala.

Det har under projektets forløb vist sig at den måske allervigtigste funktion af projektet har været at skabe et forum for videnskabelig udveksling mellem fagområder som ikke tidligere har samarbejdet om naturtilstanden i terrestriske vådområder. Et fortsat samarbejde vurderes som en forudsætning for at opnå den nødvendige vidensbasis for en omkostningseffektiv beskyttelse og forvaltning af de grundvandsafhængige terrestriske økosystemer.

Delprojekter

I løbet af projektet blev der identificeret følgende delprojekter til opfyldelse af projektets formål:

- Beskrivelse af rigkærs naturtilstand ud fra vegetationens sammensætning
- Supplerende indsamling af data om hydrologi og vandkemi fra reference-rigkær, eutrofierede vådområder og kærområder i overgangszonen mellem disse.
- Undersøgelse af sammenhængen mellem naturtilstand i rigkær og vandindvinding på Sjælland modelleret ved hjælp af DK-modellen.
- Geografisk baseret analyse af rigkærenes forekomst i ådalssystemer baseret på en kobling af data fra vandløbsovervågningen, oplandsbeskrivelser og ådalstypologi.

Metoder og resultater

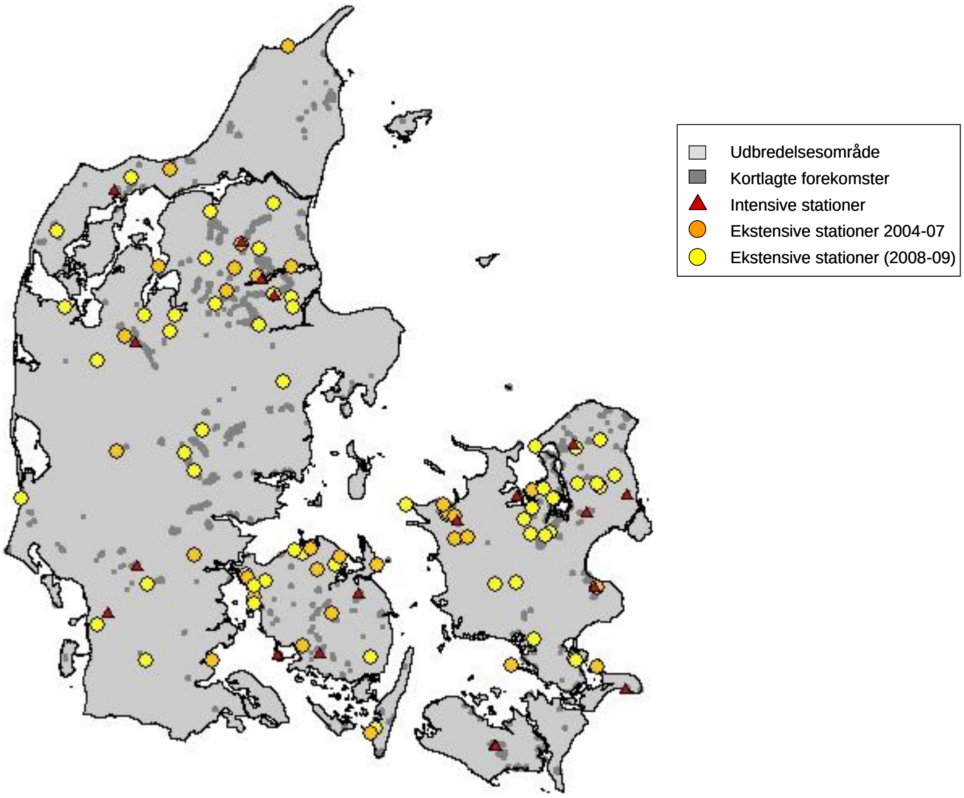
I analyserne af rigkærsdata har vi anvendt en klassifikationsmodel til ud fra artssammensætningen at adskille egentlige rigkær fra vådbundsvegetation som enten aldrig har været rigkær grundet manglende grundvandspåvirkning eller hvor eutrofieringen og/eller afvanding har medført at vegetationen har ændret sig til våde enge, fugtige enge, kulturenge eller urtebræmmer (Nygaard et al. 2009). Desuden har vi anvendt indikatorbaserede metoder til at vurdere tilstanden af rigkærene. Her har vi dels anvendt en liste over indikatorarter for gode rigkær (Tabel 2) og dels anvendt Ellenbergs indikatorværdier for fugtighed/vandstand (F), reaktionstal (R = pH) og næringsstoftilgængelighed (N) (Ejrnæs et al. 2009).

Tabel 2. Indikatorarter for velfungerende rigkær. Øverst karplanter, nederst mosser.

Dansk navn	Latinsk navn
Hjertegræs	Briza media
tvebo star	Carex dioica
skede-star	Carex hostiana
krognæb-star	Carex lepidocarpa
Alm. star	Carex nigra
loppe-star	Carex pulicaris
dværg-star, kompleks	Carex viridula s.l.
kødfarvet gøgeurt	Dactylorhiza incarnata
fåblomstret kogleaks	Eleocharis quinqueflora
sump-hullæbe	Epipactis palustris
smalbladet kæruld	Eriophorum angustifolium
Mygblomst	Liparis loeselii
Bukkeblad	Menyanthes trifoliata
Leverurt	Parnassia palustris
eng-troldurt	Pedicularis palustris ssp. palustris
Vibefedt	Pinguicula vulgaris

Tormentil	Potentilla erecta
Djævelsbid	Succisa pratensis
tvebo baldrian	Valeriana dioica
nedløbende bryum	Bryum pseudotriquetrum
fin guldstjernemos	Campylium protensum
almindelig guldstjernemos	Campylium stellatum
kalk-blødmos	Ctenidium molluscum
kær-kløvtand	Dicranum bonjeanii
kær-rademos	Fissidens adianthoides
grøn krumblad	Limprichtia cossonii
glinsende kærmos	Tomentypnum nitens

Ved at anvende Ellenbergs indikatortal som gennemsnit af de arter som forekommer i et område, typisk en cirkel med radius på 5 meter, opnås et udtryk for miljøet på voksestedet (Ejrnæs et al. 2009). Når det gælder næringsstofforureningen er det dog ikke nok at anvende Ellenbergs tal for næringstilgængelighed fordi dette tal varierer naturligt med pH, således at arter som foretrækker højere pH alt andet lige også vil have højere Ellenberg N-tal. I stedet har vi anvendt Ellenberg N divideret med Ellenberg R, et indeks vi kalder næringsratio (se også Ejrnæs et al. 2009). Antallet af indikatorarter stiger jo lavere næringsratioen er Næringsratioen (Ejrnæs et al. 2009). Næsten alle rigkær med mange indikatorarter har en næringsratio under 0,7, og rigkær med en næringsratio over 0,9 har sjældent nogle indikatorarter.



Figur 1. Kortlagte og overvågede rigkær i Danmark. Farvede symboler viser overvågningsstationer (NOVANAs terrestriske delprogram), grå markeringer viser kortlagte rigkær indenfor Natura 2000 områderne. Fra Ejrnæs et al. 2009.

Placeringen af rigkær i landskabet

- Rigkær forekommer fortrinsvis, men ikke udelukkende nord og øst for israndslinien (fig. 1). Kortet viser kun en kortlægning af rigkær inde i habitatområderne, men giver alligevel et indtryk af de danske forekomster.
- Placeringen i landskabet betinges af udstrømmende grundvand og rigkær findes derfor oftest lavt i terrænet, i ådale og kystområder.

Vi har i projektet koblet data fra NOVANA-overvågningen af vandløbsnære arealer (delprogram for ferskvand) og deres oplande i et GIS for at undersøge betingelserne for forekomst af rigkær i ådalene. Vegetationsundersøgelser blev foretaget i 2004 og 2005 på 454 vandløbsnære arealer (afgrænset som et område 100 m langs vandløbet og 30 ind på det tilliggende areal). Arealerne er repræsentative for den del af de vandløbsnære arealer i Danmark der ikke er i omdrift eller med vedvarende græs. Undersøgelserne blev foretaget på begge sider af vandløbet indenfor et areal på 2x300 m i plots på 10x10m. På nogle arealer var der veje, marker eller andet der bevirkede at færre end 30 plots blev udlagt. I alt blev vegetationsundersøgelser foretaget i 21.401 plots. Vegetationsdata blev efterfølgende klassificeret til de mest sandsynlige plantesamfund (Nygaard et al. 2009). Resultatet af klassifikationen vises i tabel 3.

Tabel 3. Oversigt over hyppighed og sårbarhed af naturtyper på 454 repræsentative vandløbsnære arealer i Danmark som ikke er med vedvarende græs eller i omdrift. 1) angiver at naturtypen er omfattet af Habitatdirektivet (habitattypekoden er vist efter samfundets navn). Plantesamfundenes sårbarhed overfor ændringer i miljøet er angivet: ***=ekstremt sårbar, ****=sårbar, ***=moderat sårbar, **=robust og *=meget robust (efter Nygaard et al. 2009).**

Naturtyper	Hyppighed i %	Sårbarhed
Kultureng	17	*
Næringsrig højstaude	16	*
Fugtig eng	12	**
Fugtig brakmark	11	*
Tør brakmark	10	*
Urtebræmme[1] (HD 6430)	9	Ukendt
Våd eng	9	***
Rigkær[1] (HD 7230)	8	*****
Sumpet bræmme	3	*
Tidvis våd eng[1] (HD 6410)	3	****
Å-mudderbanke[1] (HD 3270)	<1	Ukendt
Våd hede[1] (HD 4010)	<1	****
Hængesæk[1] (HD 7140)	<1	****
Avneknippemose[1] (HD 7210)	<1	****
Fattigkær	<1	****

Selvom blot 8% af de 21.400 prøvefelter blev klassificeret til rigkær, forekom naturtypen på 29% af de 454 repræsentative vandløbsnære arealer. Efterfølgende blev der lavet en logistisk regressionsmodel med det formål at forudsige forekomsten af rigkær på vandløbsstrækningen ud fra karakteristika i oplandet til vandløbsstrækningen, herunder oplandsstørrelse, geologisk udgangsmateriale, arealanvendelse, andel af lavbundsjorde samt afvandingen i oplandet. Vi har valgt denne tilgang fordi aktiviteter i oplandet enten direkte ved at påvirke mængde og kvalitet af det grundvand der strømmer til eller indirekte via oversvømmelsesvand fra vandløbet kan have indflydelse på vegetationen på det vandløbsnære areal.

Der blev opstillet modeller baseret på informationer indenfor hele oplandet samt indenfor zonerne 500 m, 100 m og 50 m fra vandløbet. Ligeledes blev der opstillet en model hvor kun informationer indenfor et 100 x 100 m område umiddelbart opstrøms stationen blev medtaget. Endelig blev der opstillet en model ved udvælgelse af de parametre der, uafhængigt af skala, gav den bedste forudsigelse (Tabel 4).

Tabel 4. Resultat af logistisk regressionsanalyse. Parametre blev fundet med anvendelse af forward selektion. Tabellen viser en oversigt over de betydende parametre i modellen rangordnet efter faldende signifikans. Den globale model omfatter alle stationer mens subset modellen bygger på en tilfældig delmængde af stationer.

Andelen af korrekt klassificerede rigkær er angivet i procent. Subset modellen blev krydsvalideret på den delmængde af stationer der ikke var medtaget i modeludviklingen. Et negativt estimat angiver en positiv indvirkning på forekomst af rigkær mens et positivt estimat angiver en negativ indvirkning på forekomst af naturtypen rigkær, hvilket er angivet i parentes efter estimatværdien.

Parameter	Estimat	SE	X^2	P
Afvanding_opland	0,0462 (-)	0,0103	20,14	P<0,0001
Våd åben natur_opstrøms areal	-0,0441 (+)	0,0131	11,26	P=0,0008
Lavbundsjorde_50 m zone	-0,0204 (+)	0,0064	10,06	P=0,0015
Befæstet_opland	0,0850 (-)	0,0304	7,81	P=0,0052
Omdrift_opstrøms areal	0,0134 (-)	0,0049	7,42	P=0,0064
Våd åbne natur_opland	0,35670 (-)	0,1512	5,57	P=0,0183
Omdrift_100 m zone	0,0153 (-)	0,0070	4,75	P=0,0293
Global model (n=404) X^2=153, p<0,0001; r^2=0,66				
Subset model (n=227) X^2=76, p<0,0001; korrekt klassificerede: 67%				

Vi kan ved hjælp af oplandskarakteristika med 67% sandsynlighed prædiktere forekomst af rigkær på vandløbsnære arealer i Danmark. De signifikante parametre peger tydeligt på at både oplandsrelaterede forhold samt mere lokale forhold spiller en rolle for hvor der findes rigkær i Danmark (tabel 4). Det er interessant at det er afvandingen i hele oplandet, og ikke kun det nære opland i fx 50, 100 eller 500 m zoner, der identificeres som den vigtigste parameter i modellen. Det afspejler formentlig at den mængde vand der strømmer til det vandløbsnære areal er væsentlig mindre når hele oplandet drænes og at denne reduktion er afgørende for at grundvandstilstrømning og strømningsmønstre på det vandløbsnære areal ændres således at betingelserne for forekomst af rigkær bliver ringere.

Modellen identificerer kun to parametre der har positiv indflydelse på sandsynligheden for at finde rigkær på det vandløbsnære areal nemlig andelen af lavbundsjord i det nære opland (50 m) samt andelen af våd natur umiddelbart opstrøms det vandløbsnære areal. Sandsynligheden for at finde rigkær øges altså når der er meget natur i nærheden. Høj tæthed af natur og lavbundsjord peger på at de hydrologiske forudsætninger er til stede og at området ikke er taget i intensiv landbrugskultur. Tilsvarende kan den negative betydning af omdrift både opstrøms og i det nære opland (100 m) indikere at næringsstoffer og måske pesticider er medvirkende til at ændre kårfaktorerne på de vandløbsnære areal så de ikke længere kan understøtte forekomst af rigkær.

Supplerende dataindsamling

Den supplerende dataindsamling blev foretaget på 18 stationer: 15 ekstensive stationer hvor der blev målt vandstand i april og august og indsamlet vandprøver til måling af pH, nitrat, ammonium og fosfat samt tre intensive stationer hvor der blev taget prøver til vandkemi i juli 2008 og opsat dataloggere til vandstandsmålinger (fig 2).

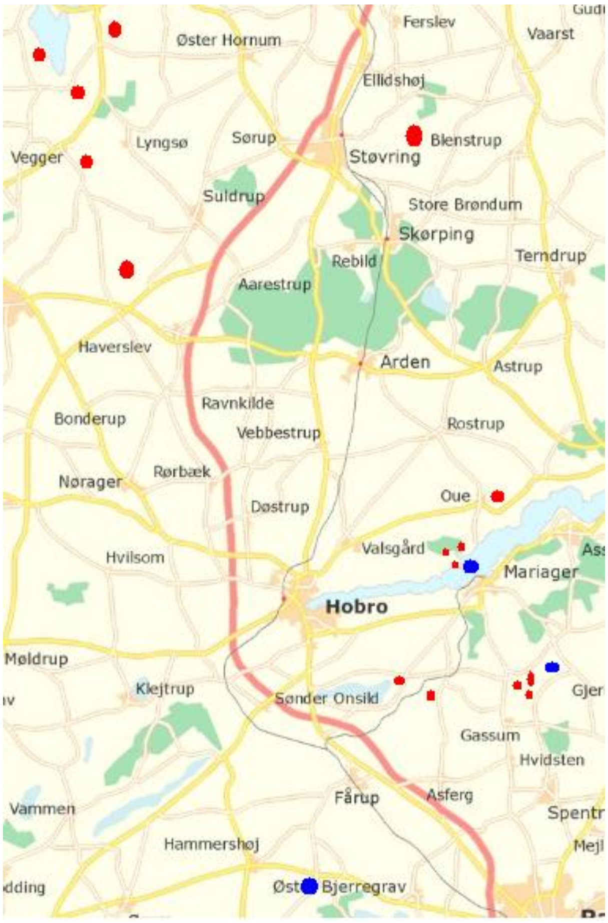


Fig 2. Placeringen af intensive (blå) og ekstensive målestationer (røde) i økohydrologiprojektet

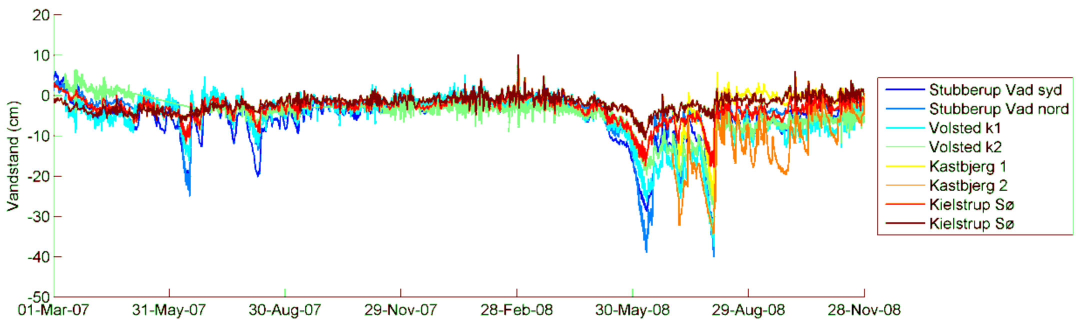
De 18 stationer blev udvalgt med det formål at beskrive hydrologiske og vandkemiske forskelle mellem velfungerende rigkær på den ene side og mosevegetation med aftagende grundvandspåvirkning og/eller markant eutrofiering på den anden. Eftersom de velfungerende rigkær er langt sjældnest blev stationerne udvalgt ved at foretage en screening af samtlige dokumenterede rigkær fra NOVANA's naturtypeovervågning og DEVANO's naturtypekortlægning i habitatområderne. Ved screeningen udvalgte vi prøvefelter (5m-cirkler) fra våd bund med en næringsratio under 0,7 samt en vegetation som svarede til rigkær i moseklassifikationsmodellen. Endvidere indgik praktiske overvejelser om tilgængelighed og logistik, herunder køretid og tilladelse fra lodsejer. Bruttolisten over områder viste en særlig høj koncentration af de gode rigkær nord for Århus, særligt syd for Mariager Fjord samt i Østhimmerland mellem Mariager Fjord og Limfjorden. Stationerne endte også med at blive placeret i dette område. På hver lokalitet blev der, baseret på vegetationens sammensætning, foretaget en subjektiv afgrænsning af rigkærets udstrækning og etableret prøvetagning i rigkærets centrum, rigkærets periferi, samt i et vådt næringsbelastet område udenfor rigkæret. Tabel 5 viser de udvalgte lokaliteter og den gennemsnitlige næringsratio for centrum, periferi og næringsbelastet område.

Tabel 5. De 18 stationer med gennemsnitlig næringsratio fra vegetationen i 5m-cirkler i de tre forskellige prøvetagningszoner.

	Næringsbelastet	Periferi	Centrum
Dyrby Krat	0.94	0.75	0.66
Glenstrup Sø	0.83	0.81	0.78
Halkær Bredning	0.97	0.78	0.65
Halkær Sø	0.9	0.74	0.65
Kastbjerg Å "lav"	0.89	0.8	0.78
Kielstrup Sø, "pilekrat-kant"	0.82	0.75	0.71
Kielstrup Sø Nord	0.84	0.72	0.66
Kielstrup Sø "pilekrat"	0.82	0.73	0.7
Klæstruplund	0.94	0.78	0.7
Lambækdal		0.77	0.67
Mosbæk	0.88	0.82	0.7
Oue	0.88	0.74	0.71
True	0.98	0.76	0.65
Vegger	0.91	0.76	0.74
Volsted	0.86	0.77	0.71
Kastbjerg ”intensiv”	0.80	1.04	0.68
Kielstrup Sø ”intensiv”	1.02	0.75	0.69
Læsten ”intensiv”	1.01	0.82	0.83

Hydrologisk karakterisering af rigkær

Rigkær er karakteriseret ved en konstant udstrømning af grundvand og derfor også ved en relativ konstant vandstand i kontakt med overfladen af tørven det meste af året - undtaget sommermånederne, hvor der kan ses en større eller mindre sænkning. Vi har i økohydrologiprojektet haft vandstandsloggere på fire stationer, og vi har i nedenstående figur 3 suppleret disse med loggere på to NOVANA-overvågningsstationer. Figuren viser at rigkærene har en meget stabil vandstand tre fjerdedele af året, men i sommermånederne juni-august, kan der optræde større eller mindre sænkninger af vandstanden, typisk med blot 10 cm, men i visse tilfælde op til 40 cm. Sammenlignet hermed vil vandstanden fluktuere langt mere, og typisk gennem hele året, i mosetyper som domineres af tilstrømmende overfladevand eller regnvand.

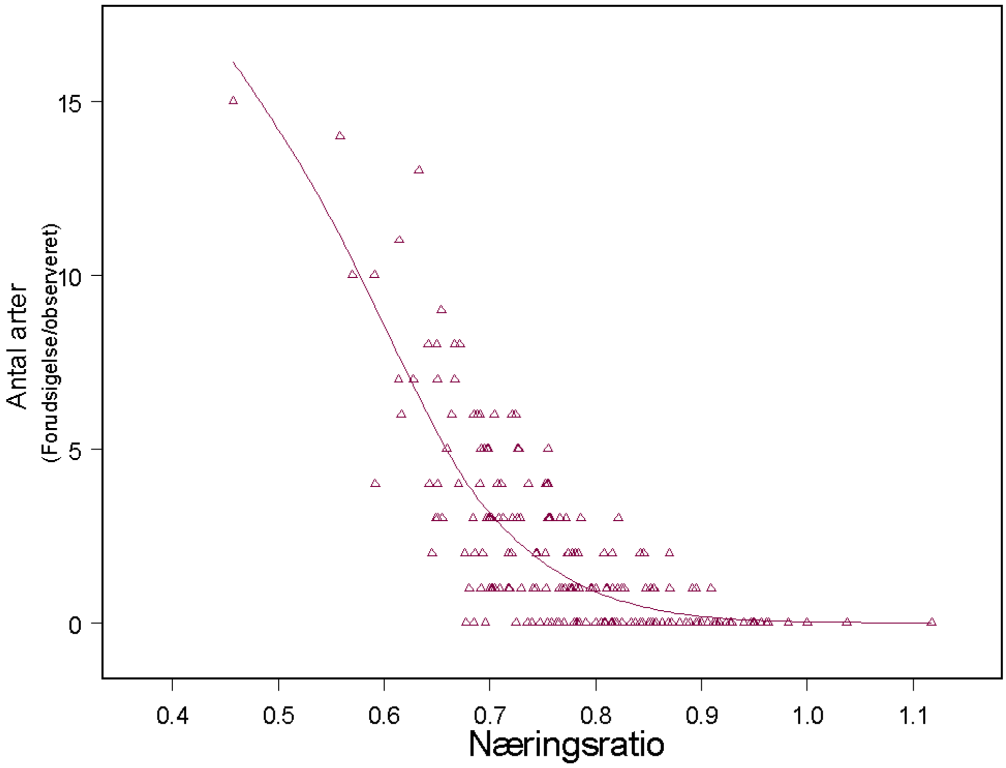


Figur 3. Vandstandsfluktuationer fra 8 rigkærslokaliteter med vandstandsloggere.

Der er ikke foretaget en kortlægning og hydrologisk modellering af stationerne i økohydrologiprojektet og i NOVANA, men det er en nærliggende hypotese at forskellen mellem lokaliteterne i figuren kan afspejle lokalitetsspecifikke kontaktforhold til det omgivende grundvandsmagasin og overfladevandssystemer.

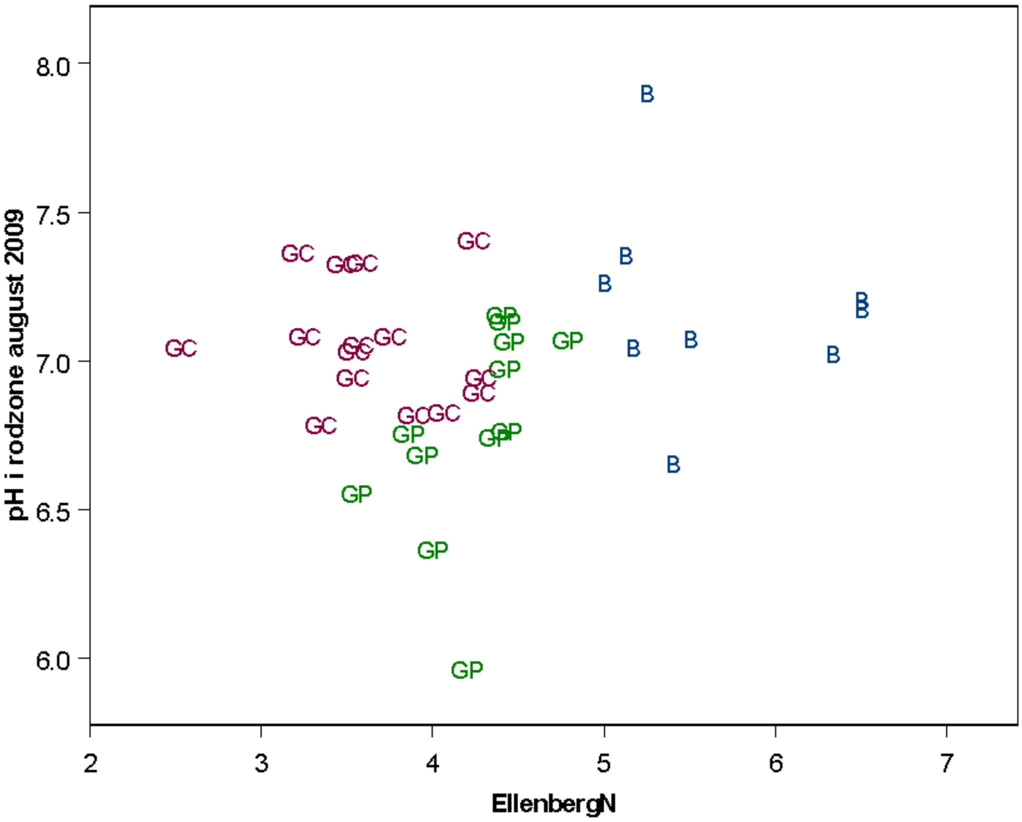
Kobling af vandkemi og biologisk tilstand af rigkær

Formålet med de vandkemiske undersøgelser var at undersøge om indholdet af næringsstoffer i vandet kunne forklare forskellene mellem velfungerende rigkær og dårlige områder uden indikatorarter, samt områder i periferien af de velfungerende rigkær. Indledningsvist undersøgte vi om den tidligere beskrevne korrelation mellem næringsratio og antallet af gode indikatorarter for velfungerende rigkær (Ejrnæs et al. 2009) også var gældende for prøvefelterne i økohydrologi-projektet. Figur 4 viser at dette er tilfældet, idet et højt antal indikatorarter kun forekommer ved en næringsratio under 0,7 samt at indikatorarterne er stærkt decimeret ved 0,8 og helt væk ved 0,9.



Figur 4. Sammenhæng mellem næringsratio og antal indikatorarter. En non-lineær regressionslinje er tilføjet til data og viser det gennemsnitlige antal arter ved en given næringsratio.

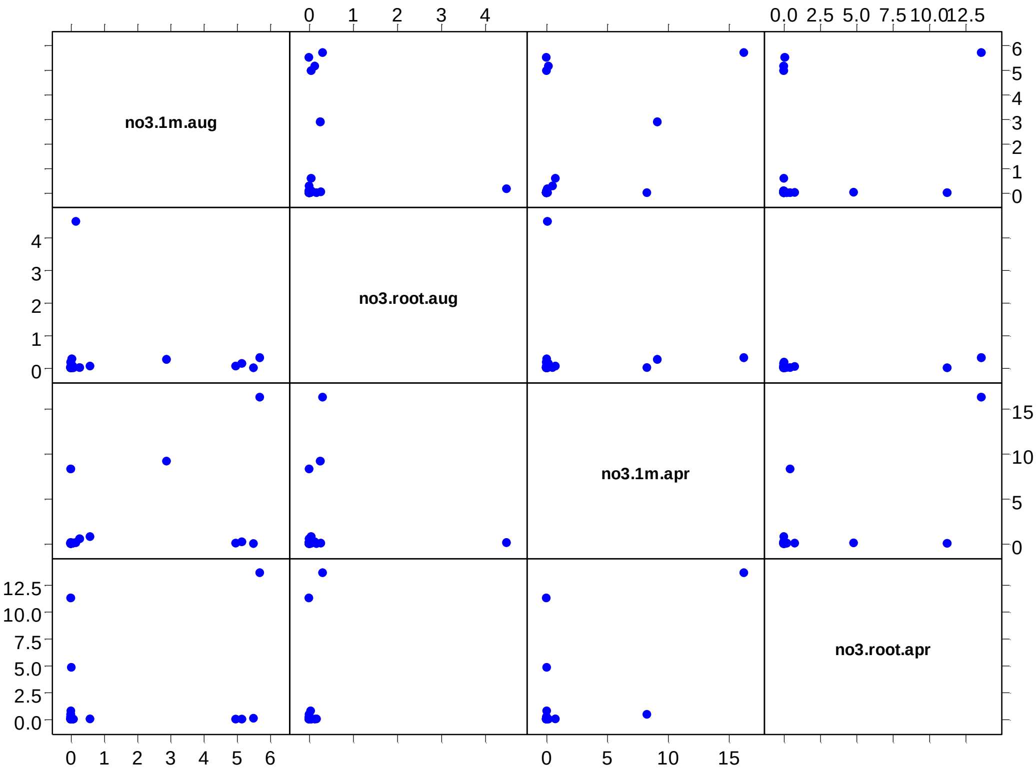
Vi forsøgte at udlægge områderne så alle var tydeligt påvirkede af en høj vandstand. I felten kunne vi imidlertid ikke kontrollere pH, og da pH er en stærk plantefordelende faktor var det interessant at sammenligne de tre forskellige områdetyper for denne faktor. Figur 5 viser at selvom der er tydelig forskel på de gode og dårlige områders værdier for Ellenberg N (afledt af vegetationen), så er pH i høj grad sammenlignelig mellem de gode rigkærsområder (GC) og de dårlige områder (B). Områderne i periferien af de gode rigkær (GP) har en tendens til en lidt lavere pH, hvilket svarer til den forventede effekt af en aftagende grundvandsudstrømning.



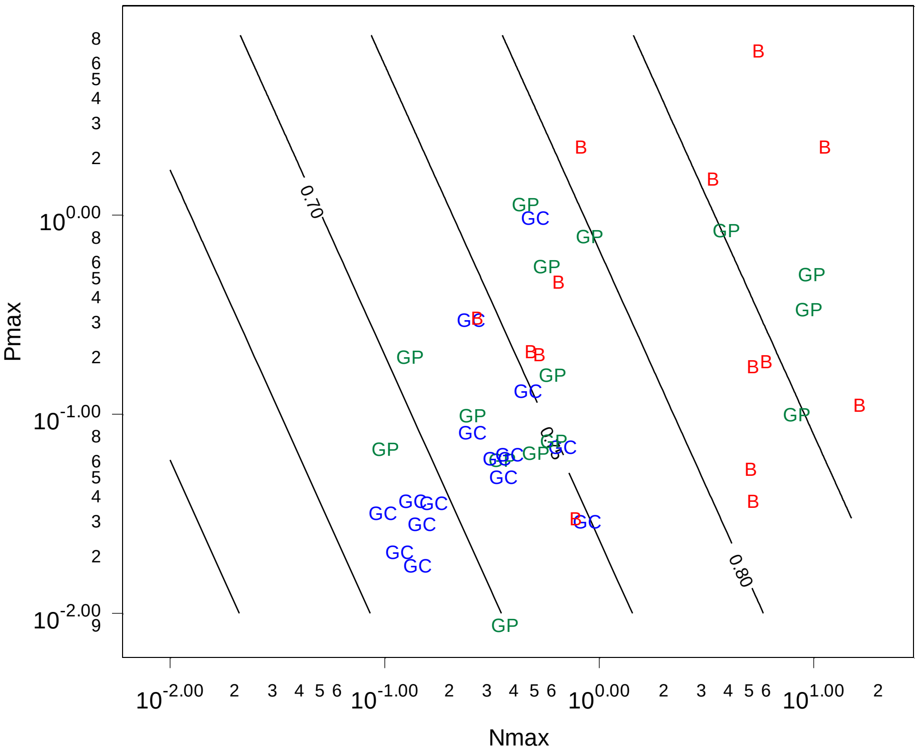
Figur 5. De undersøgte lokaliteters pH vist mod vegetationens næringsstatus udtrykt ved Ellenbergs indikatorværdi for næringsstoffer (Ellenberg N). GC = centrum af gode områder, GP = periferien af gode områder, B = dårlige områder.

Der blev sat piezometerrør i rigkærscentrum og –periferi med filter i hhv. rodzone og 1 m under terræn. I dagene inden prøvetagning blev rørene tømt, så friskt vand kunne løbe til. Der blev udtaget vandprøver 29. april- 1. maj og igen 17. – 19.august. Alle prøver blev analyseret for fosfat (PO4-P), ammonium (NH4-N) og nitrat (NO3-N). I august blev der desuden målt pH og ledningsevne. Analyser af sammenhænge mellem biologiske indikatorer for naturtilstand (indikatorarter, næringsratio, Ellenberg F, R, N) og målte næringsstofkoncentrationer viste at de stærkeste korrelationer blev opnået med de maximalt målte værdier ved prøvetagningsstedet for begge dybder og tidspunkter. Dette skyldes at der er meget stor variation i næringskoncentrationerne afhængig af årstid og prøvetagningsdybde, således at en enkeltstående måling kun har en mindre sandsynlighed for at diagnosticere et næringsbelastet miljø (fig. 6).

Figur 7 viser fordelingen af prøvefelter i forhold til maximalt målte koncentrationer af N og P og næringsratio beregnet ud fra sammensætningen af arter i prøvefeltet. Konturlinjerne i figuren viser forudsigelsen fra en multipel regressionsmodel af næringsratio som funktion af max N og max P. Der er en signifikant forskel mellem de tre områdetyper, således at de højeste koncentrationer af næringsstoffer generelt er målt i områder med en dårlig biologisk tilstand og de laveste max-værdier i centrum af rigkærene. Periferien af rigkærsområderne har intermediære værdier, men med en stor spredning. Centrum af de gode rigkær har maximale koncentrationer under 1 mg N/liter og under 1 mg P/liter.



Figur 6. Fire prøver af nitrat-N koncentrationer plottet mod hinanden i en matrix-figur. Figuren skal læses som en tabel hvor hver af cellerne viser et plot af målte nitratværdier for de variabler som hører til i den pågældende række og kolonne. Variablerne står i diagonalen og er, startende øverst til venstre: prøve fra 1 m. dybde i august, prøve fra roodzone i august, prøve fra 1 m. dybde i april og prøve fra rodzone i april.



Figur 7 viser hvordan næringsratio afhænger af N-max og P-max (begge i mg/l PO4-P eller NO3-N/NH4-N. Konturlinjerne i figurerne stammer fra den bedste generaliserede additive model som viste sig at være næringsratio modelleret som en logaritmisk funktion af Nmax og Pmax. Konturlinjerne viser modellens forudsigelse af effekten af N og P på vegetationens næringsratio. GP= periferi, GC=centrum og B=dårlig område.

Vi finder altså en signifikant sammenhæng mellem max N og max P og den biologiske tilstand, men også betydelig variation. Figur 7 viser den bedste fundne sammenhæng som forklarer ca. 30% af variationen i den biologiske tilstand udtrykt ved næringsratioen. Hvis vi alene analyserer for N max, som har langt den stærkeste effekt på næringsratioen, viser både modelforudsigelsen og modellens konfidensgrænser (figur 8) at den gode tilstand (næringsratio < 0,7) findes ved N-max værdier under 0,3 mg N/liter, hvilket svarer til ca. 1,3 mg nitrat/liter. Der er dog, som man kan se på figuren, stor variation, og to rigkær med næringsratio < 0,7 har N-max op i nærheden af 1 mg N/l. Begge disse felter har dog relativt lav fosforværdier.

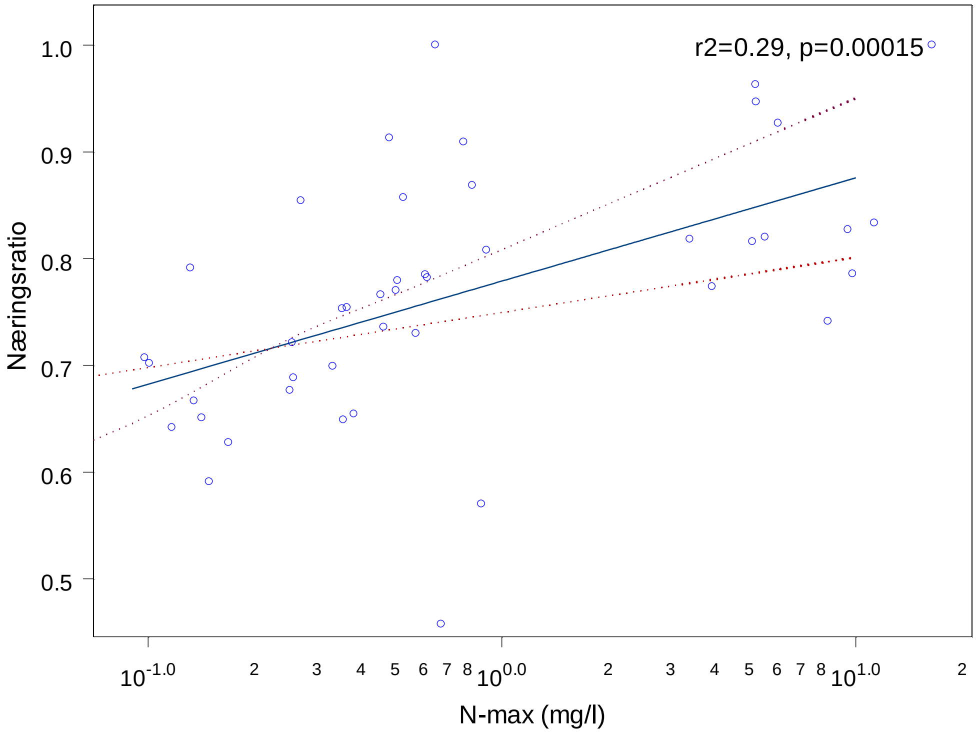


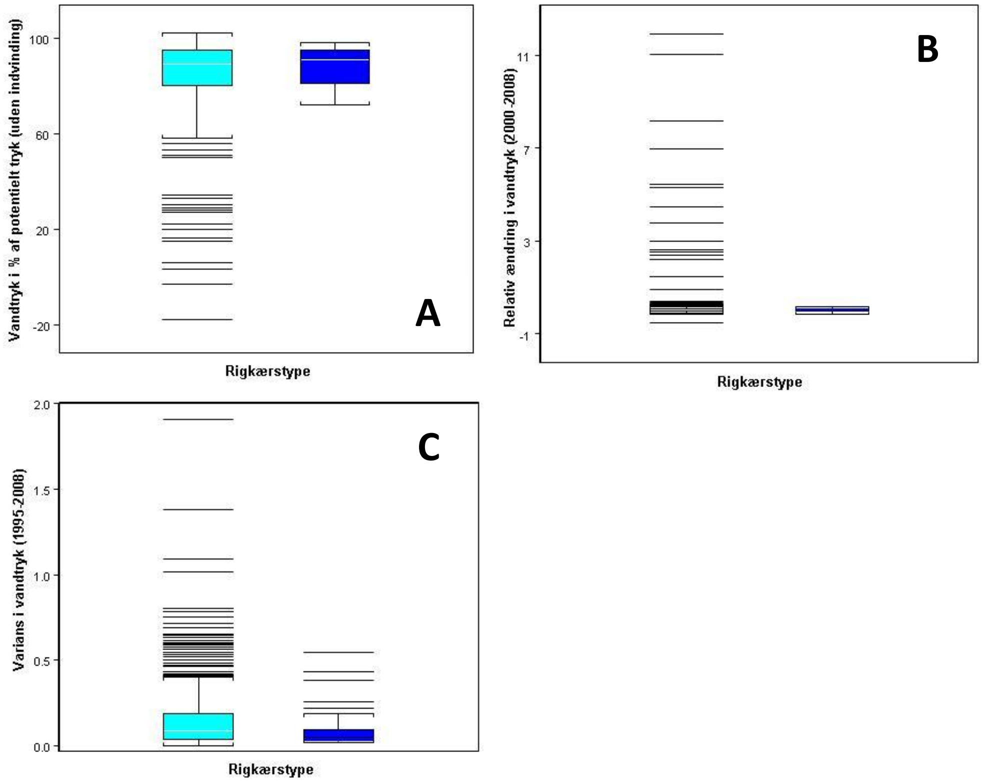
Fig 8. En model af næringsratioen som lineær funktion af logaritmen til den maximalt målte koncentration af uorganisk kvælstof i vandprøverne. Modellens forudsigelse er vist med fuldt optrukken linje, øvre og nedre 95% konfidensgrænser på model-koefficienterne er vist med stiplede linjer. De aktuelle målinger er vist på figuren.

Kobling af grundvandsmodel og sjællandske rigkær

GEUS har udviklet en landsdækkende vandressource model, DK-modellen, som baseret på bl.a. boringsdata, indvindingsoplysninger og meteorologiske data kan simulere det hydrologiske kredsløb med særlig fokus på grundvandssystemet (Højberg et al. 2008). Modellen kan således simulere grundvandsniveauet i forskellige geologiske lag med en opløsning på 500 x500 m. I dette projekt er kun arbejdet med delmodellen dækkende Sjælland, da modellen for resten af landet ikke har været færdigopdateret. Fokus i projektet har været på det dybe reducerede grundvand i kalken af tre årsager: For det første er det dette lag hvorfra størstedelen af vandindvindingen finder sted, og derfor også her man kunne forvente at se en effekt af vandindvindingen. For det andet er det også de dybe grundvandsmagasiner som DK-model Sjælland bedst kan beskrive. For det tredje er rigkærene afhængige af tilstrømning af baserigt, næringsfattigt og reduceret grundvand fra de dybe kalkmagasiner. Simulerede trykniveaudata for hver 30. dag for perioden 1995-2008 er anvendt for både en situation hvor indvindingerne er aktive og en hvor alle indvindinger er fjernet.

Det blev undersøgt, om grundvandsniveauet i 500 x 500 m cellerne på nogen måde co-varierede med forekomsten og tilstanden af de sjællandske rigkær, men, ikke overraskende, viste der sig ikke at kunne påvises nogle sammenhænge. Modellens opløsning er antageligt for lille til en sådan analyse. En lokal modellering af grundvandstryk med inddragelse af topografi har ikke været muligt at foretage i projektet.

Dernæst undersøgte vi om der var en sammenhæng mellem ændringer i grundvandsniveauet som følge af vandindvinding og forekomsten og tilstanden af de sjællandske rigkær. Dette gjorde vi ved at beregne den procentvise grundvandssænkning som følge af vandindvinding i 500 x 500 m cellerne samt beregne ændringer i grundvandsstanden gennem de seneste 8 år udtrykt som den relative trykændring fra 2000 til 2008. Vi undersøgte om der var forskel på rigkær i optimal tilstand (naturtype enten rigkær, hængesæk eller tidvist våd eng, Ellenberg R > 5, næringsratio < 0,7 og > 5 indikatorarter for rigkær) og øvrige rigkær (samme naturtyper og Ellenberg R kriterium).



Figur 9. Tre box-plots som viser fordelingen af prøvefelter fra gode rigkær (højre, turkis box) og øvrige rigkær (venstre, mørkeblå box). De blå bokse viser placeringen af den midterste halvdel af datapunkterne, medianværdien vises med hvid stribe, stigerne viser 1,5 x øvre og nedre kvartil og linjerne viser ekstreme værdier udenfor dette interval. Delfigurerne viser: A) det gennemsnitlige vandtryk i 2008 i procent af vandtrykket uden vandindvinding (p=0,9), B) den relative ændring af vandtrykket i perioden 2000-2008 (p=0,09) og C) variansen i det månedlige vandtryk for perioden 1995-2008 (p<0,001). Alle tests = Wilcoxon rank sum test.

Analysen viste at de gode rigkær generelt forekommer i områder hvor vandindvindingen har en mindre effekt (fig. 9A), hvor vandtrykket har været stabilt i perioden 2000-2008 (fig. 9B) samt hvor vandtrykket varierer mindre fra måned til måned (fig. 9C). Det var dog kun forskellen i variansen af vandtrykket som var signifikant.

Ændringer i rigkærenes biologiske tilstand 2004-2009

Vi har anvendt data fra naturtypeovervågningen i NOVANA til at undersøge om vi kan observere ændringer i rigkærenes tilstand i Danmark gennem denne 6-årige periode. Vi har filtreret data på følgende måde:

1) Kun prøvefelter som er overvåget minimum 3 år i perioden 2004-2009 er medtaget
2) Kun prøvefelter med gennemsnitlig Ellenberg R > 5 er medtaget (kalkpåvirkning)
3) Kun prøvefelter hvor 75% af gentagelserne mellem årene er klassificeret til en potentielt grundvandspåvirket mosetype i mosemodellen er medtaget. Som grundvandspåvirkede

mosetyper er medtaget fattigkær, tidvis våd eng (6410), hængesæk (7140), avneknippemose (7210), rigkær (7230) som opfylder ovenstående kriterier.

4) To prøvefelter med overvægt af fattigkær blev sorteret fra analysen.

De tilbageværende ”grundvandspåvirkede” naturtyper blev dernæst inddelt i 3 kategorier: Fine, medium og ringe. ”Fine” er prøvefelter med gennemsnitlig næringsratio som ikke overstiger 0,7 og gennemsnitlig antal indikatorarter > 5. ”Ringe” er prøvefelter med gennemsnitlig næringsratio > 0,8. ”Medium” er resten.

Vi undersøgte om der var signifikante ændringer i rigkærenes Ellenberg-gennemsnit for næringsstatus (N) og fugtighed (F). Dette blev undersøgt for både alle rigkærene og særskilt for hver af de tre kategorier af rigkær. De bedste modeller over ændringerne gennem årene inkluderede autokorrelation og der var ikke signifikante ændringer i overvågningsperioden for nogle af rigkærsgrupperne. Der var dog en tendens til at de bedste rigkær har stigende Ellenberg N-gennemsnit gennem den 5-årige periode (fig. 10), hvilket kunne tyde på at der sker en eutrofiering via ændringer i grundvandets mængde eller kemiske sammensætning.

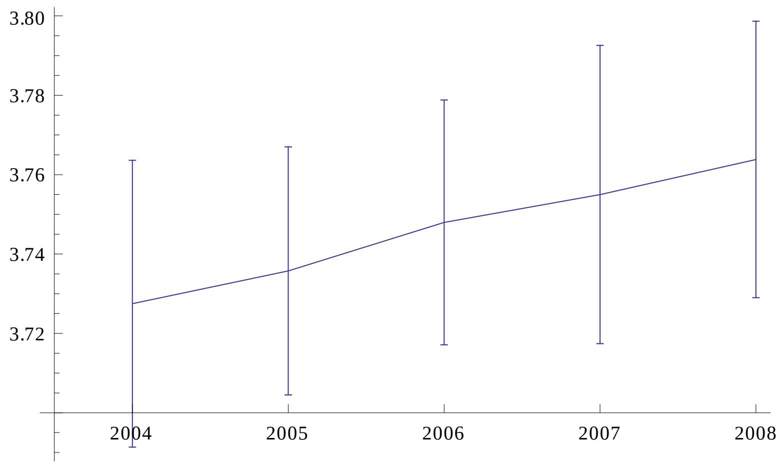


Fig 10. Udviklingen i Ellenberg N gennem overvågningsperioden for de ”fine” rigkær med en vegetation som indikerer en god tilstand. Linjen går gennem middelværdierne for årene og stolperne viser 95%-konfidensgrænserne på middelværdierne.

Sammenfatning

Økohydrologi-projektet har for første gang i NOVANA's levetid bragt hydrologer, terrestriske økologer, ferskvandsbiologer og grundvandseksperter sammen i studiet af de grundvandsbetingede terrestriske økosystemer. Projektets formål var at undersøge ubeskrevne koblinger mellem data fra NOVANA's delprogrammer for grundvand, overfladevand og terrestrisk natur samt at foretage en supplerende dataindsamling til at belyse de hydrologiske og vandkemiske forudsætninger for en god økologisk og biologisk tilstand af de grundvandsafhængige terrestriske økosystemer. På denne baggrund skulle projektet komme med anbefalinger til revisionen af NOVANA.

Projektet har fokuseret på naturtypen rigkær, som kan defineres som stærkt næringsbegrænset, men artsrig, terrestrisk vegetation domineret af mosser, halvgræsser og bredbladede urter og betinget af en stadig gennemstrømning af kalkrigt og næringsfattigt grundvand. Endvidere er rigkær i større eller mindre grad afhængige af tilbagevendende forstyrrelser i form af græsning eller høslæt for ikke at gro til med pil og el. Naturtypen har en ekstremt begrænset udbredelse i dag som følge af afvanding og næringsforurening samt ophørt græsning og høslæt og den rummer mange sjældne arter af planter, mosser og invertebrater.

Koblingen og analyserne af eksisterende data fra de forskellige delprogrammer i NOVANA har ført til:

- Udviklingen af modeller til klassificering og tilstandsvurdering af rigkær ud fra deres vegetation. Disse modeller egner sig til hurtig og omkostningseffektiv screening af store datasæt, udvælgelse af områder til overvågning og analyse og vurdering af tilstand og følsomhed over for påvirkninger udefra (fx tabel 2+3+5, fig. 4).
- Demonstration af rigkærenes følsomhed overfor afvanding i oplandet gennem GIS-analyser og analyser af DK-modellen og kvaliteten af de sjællandske rigkær (tabel 4).
- Demonstration af rigkærenes afhængighed af en konstant tilførsel af grundvand som kan opretholde en stabil vandstand i hovedparten af året (fig. 3+9).

Endvidere har den supplerende dataindsamling i projektet og analyserne af disse data vist at:

- Der er en signifikant sammenhæng mellem vegetationen i rigkærene og vandprøvernes indhold af uorganisk kvælstof og fosfor (fig. 7+8).
- Der er store variationer i næringsstofmålingerne afhængig af dybden og årstiden (fig. 6).
- De bedste af de undersøgte rigkær forekommer ved et maximalt nitrat-N-indhold < 0,3 mg/l (1,3 mg NO3/l), hvilket ligger langt under de eksisterende grænseværdier for nitrat i drikkevand (50 mg NO3/l) (fig. 7+8).

Anbefalinger til overvågning

Der er et betydeligt efterslæb i vores forståelse af de grundvandsafhængige terrestriske økosystemer, fordi de i store træk har været ignoreret i beskrivelsen af vandets og næringsstoffernes kredsløb i Danmark, hvor fokus har været på transporten af stoffer til overfladevandsrecipienter. Selvom vi kan lære meget ved at studere udenlandske forskningsresultater og udredninger, vil det være nødvendigt at opbygge en dansk kompetence også hvis vi vil opfylde direktivernes forpligtelser om beskyttelse og målrettet forvaltning af de grundvandsafhængige terrestriske økosystemer.

På baggrund af resultaterne i økohydrologiprojektet anbefales det at overveje følgende i forbindelse med revisionen og udarbejdelsen af nye tekniske anvisninger til næste periode af det nationale overvågningsprogram NOVANA:

Omkring planlægningen af økohydrologiske overvågningsstationer:

At sikre synergien mellem delprogrammerne ved at etablere fælles overvågningsstationer for terrestriske grundvandsafhængige økosystemer hvor der indsamles sammenhørende data om biologi, hydrologi og vandkemi.

At udnytte en kombination af intensive stationer med detaljeret kortlægning og overvågning af hydrologi, vandkemi og stofkredsløb og ekstensive stationer med overvågning af udvalgte nøgle-indikatorer til at sikre en balance mellem økosystemforståelse og repræsentativitet.

Omkring udvælgelse af økohydrologiske overvågningsstationer:

At fokusere første fase af overvågningen på rigkær (habitattype 7230), med inddragelse af kildevæld (7220), tidvis våde enge (6410) og hængesæk (7140), hvor der forekommer tydeligt grundvandspåvirket vegetation.

At udnytte vegetationsdata fra NOVANA-overvågning 2004-2009 til stratificeret udvælgelse af egnede overvågningsstationer.

At placere målepunkter sammen med eksisterende prøvefelter på overvågningsstationer i det terrestriske delprogram som er gennemført i 2004-2009 for at kunne koble status og udvikling i naturens tilstand til de hydrologiske og vandkemiske betingelser.

Omkring parameterudvælgelse:

At udnytte følgende parametre i den ekstensive overvågning: vandstandsloggere, indhold af nitrat, ammonium, fosfat og pH i rodzonen, N og P-koncentrationer i løv af udvalgte arter, sammensætningen af karplanter, bladmosser og tørvemosser.

At udnytte følgende parametre i den intensive overvågning: Parametre fra den ekstensive overvågning suppleret med Mg, Fe, Ca, S, anvendt på forskellige hydrologiske fraktioner: a) grundvand inden det passerer gennem tørven, b) grundvand i udstrømningszonen i tørven, c) grundvand nedstrøms udstrømningszonen, d) overfladevand fra vandløb/sø, e) overfladevand fra dræn. Desuden bør der foregå en kortlægning af det hydrologiske kredsløb og dets kilder på stationen og en aldersdatering af grundvandet.

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Endvidere har projektet haft et tæt samarbejde om vejledning og synergier mellem tre igangsatte phd-projekter ved:

Dagmar Kappel Andersen (AU, DMU, VIBI)

John Bøhme Dybkjær (AU, DMU, FEVØ)

Ole Munch Johansen (AAU).

APPENDIX III

ANBEFALINGER TIL MILJØCENTER ODENSE OM NATURGENOPRETNING AF HELNÆS MADE

Title: Recommendations to the Environmental Agency in Odense regarding restoration of Helnæs Made.

English summary *(not included in the original document)*

The following document is a consultancy report containing recommendations on management and restoration of the area Helnæs Made located on the Island Helnæs south of Funen, the central island of Denmark. Helnæs Made is a reclaimed land area where the water level is highly managed by a system of drainage canals connected to a pumping station. Along the edge of the area groundwater seepage takes place and supports a number of fen habitats. One of these contains the fen orchid *Liparis loeseii* which is listed in Annex II of protected species in the European Habitats Directive. An evaluation of the functioning of shallow ditches was conducted and supplementary water samples were analysed for nutrients and pH. We considered possibilities for closing drainage ditches in the area without risking stagnation of water or inundation with nutrient rich water from agricultural areas. A model-based assessment of the habitat suitability for *Liparis loeseii* was applied to the surrounding areas and resulted in concrete suggestions which would improve the conservation status and possible spreading of *L. loeseli* and fen vegetation in general.

Forvaltning af rigkær i Helnæs Made - vurdering af muligheder for hydrologisk genopretning af grundvandspåvirkede rigkær

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Baggrund

Hovedparten af den beskyttede lysåbne natur i Helnæs Made kan beskrives som rigkær – habitattype 7230. Der er dog et betragteligt overlap mellem rigkær og kalkrige kildevæld (habitattype 7220), og den følgende gennemgang kan i høj grad betragtes som fælles for de to naturtyper.

Rigkær er en lysåben naturtype, der kan opstå hvor næringsfattigt, kalkholdigt grundvand presses op til jordoverfladen og danner et fugtigt til vådt miljø, for eksempel i ådale, i klitlavninger, på skråninger, eller andre steder, hvor undergrunden er gennemtrængelig for det opstigende grundvand. Vegetationen i rigkæret er almindeligvis lavtvoksende, artsrig med mange kalkkrævende arter og oftest domineret af halvgræsser og mosser. Der vil ofte være et ret stort islæt af sjældne arter (Wassen et al. 2005).

Den konstante gennemstrømning af grundvand er af afgørende betydning for opretholdelsen af de særlige økologiske forhold i rigkærsområderne, og ligegyldigt i hvilket habitat rigkæret er opstået, er der en række vandkemiske og hydrologiske forhold, der er meget ens (Grootjans et al. 2006):Vandstanden er meget stabil hen over året sammenlignet med regnvandsbetingede mosetyper, og den vandmættede zone befinder sig ofte indenfor 10 cm fra overfladen med et mindre fald hen over sommermånederne (Boomer & Bedford 2008a). Indholdet af calcium i grundvandet er højt, og det medvirker til at stabilisere pH mellem 5,5 og 8 afhængig af undergrundens beskaffenhed og forholdet mellem grundvand og overfladevand i området (Almendinger & Leete 1998b). Foruden calcium vil indholdet af ioner som jern og mangan også være højt, og det er med til at binde fosfor, så det bliver utilgængeligt for planterne, og der skabes et næringsbegrænset miljø (Boomer & Bedford 2008b, van der Welle et al. 2008).

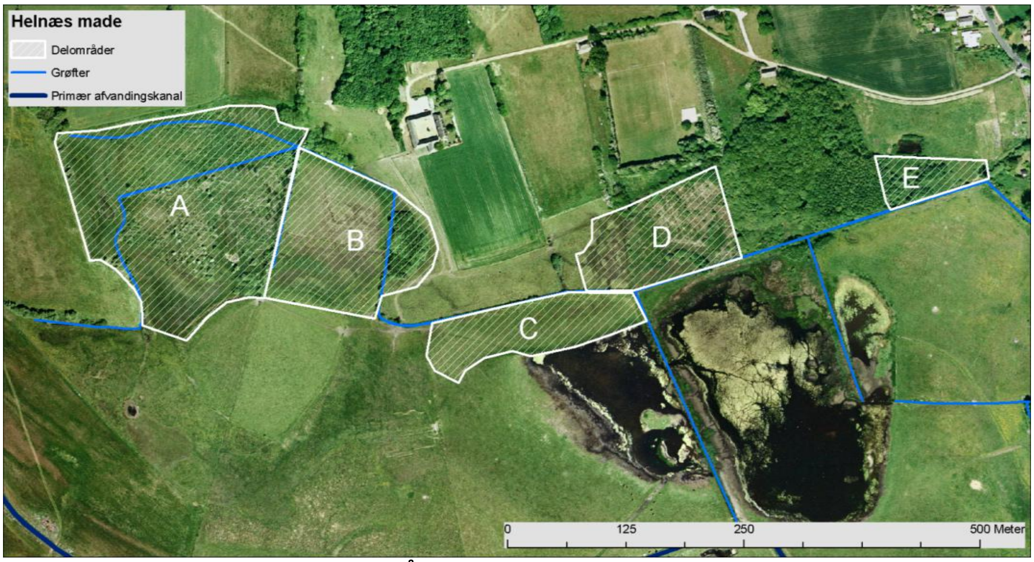
Antropogene påvirkninger af hydrologi og vandkemi har gjort rigkær til en truet naturtype i Danmark. De fleste vådområder er i større eller mindre omfang drænet, så dyrkning eller græsning er blevet mulig. Tilførsel af næringsstoffer via luft, overfladevand og tilmed grundvand forskubber balancen i rigkærene, så mere konkurrencestærke arter vinder indpas og udkonkurrerer de karakteristiske lavtvoksende arter. Dræning og indvinding af grundvand til drikkevand eller markvanding medfører selvsagt en sænkning af vandstanden og derved iltning af den ellers vandmættede tørv, der så kan nedbrydes og måske frigive næringsstoffer (Grootjans et al. 2006; Wassen and Olde Venterink 2006). De fleste danske rigkær har behov for pleje i form af græsning, slæt eller rydning af vedplanter for at bibeholde den lysåbne struktur. Samtidig er optrædning af kreaturer med til at skabe en varieret struktur med en gradient i fugtighed og åbninger i vegetationen, hvor nye planter kan etablere sig.

Projektområdet

Projektområdet er i dette projekt Helnæs Made, med fokus på de grundvandspåvirkede arealer, som findes i kanten af maden. Områderne kan opdeles i et ganske lille område mod nord, en klynge af rigkær vest og nord for Åledyb og et område i den sydøstlige del af maden. De bedst bevarede rigkærsområder findes vest og nord for Åledyb, og her forekommer blandt andet en bestand af mygblomst, som er indikator for ekstremrigkær, og som er beskyttet og opført på Habitatdirektivets bilag II (se figur 1).

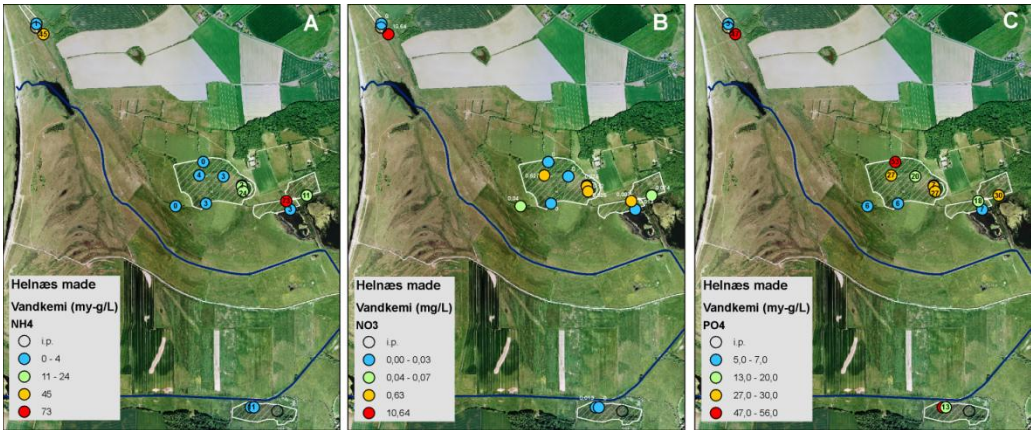
Figur 1. Oversigtskort over Helnæs Made med kortlagte rigkær (7230) og kildevæld (7220)

For gennemgangen i det følgende er rigkærene ved Åledyb opdelt i fem delområder (A-E, se figur 2). I basisanalysen for habitatområdet (prior.dmu.dk) vurderes naturtilstanden som gunstig (god), men dette dækker over at artstilstanden vurderes som gunstig (høj), mens strukturtilstanden vurderes som ugunstig (moderat). Ser man på indikatorerne for forvaltningen, peger basisanalysen på, at græsning/slæt er utilstrækkelig, og at der tillige er tilgroning med vedplanter og en ikke-optimal hydrologi i områderne. Denne vurdering blev bekræftet under besigtigelsen i marts 2011, hvor det tydeligt fremgik at græsningstrykket mange steder var for lavt med markant ophobning af førne fra forrige års vækst.



Figur 2. Oversigt over rigkær nord og vest for Åledyb (delområde A-E)

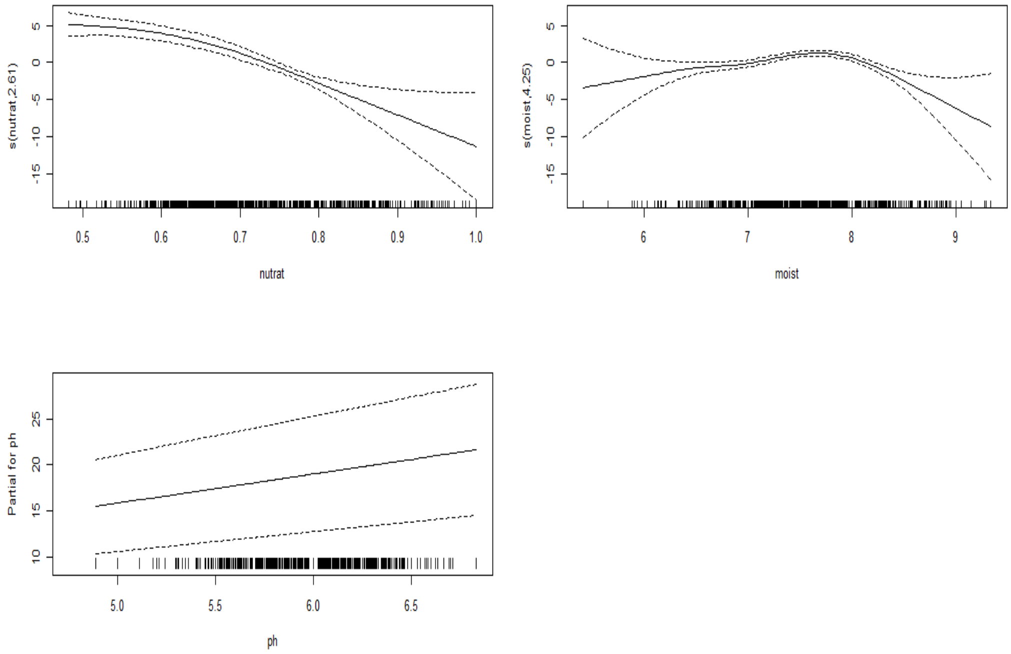
Ved besigtigelse 22. marts 2011 blev der taget vandprøver i piezometerrør, grøfter samt et drænrør (figur 3A-C). Der blev udelukkende fundet høje værdier for nitrat i drænrøret. Økohydrologiprojektet (Ejrnæs et al. 2010) foreslår en grænseværdi for nitrat-N i rigkær og kildevæld på 0,3 mg/l, og højeste værdi målt i grøfterne som omkranser rigkærene er 0,6 mg/l. For fosfat i vand, er grænserne mindre klare, men økohydrologiprojektet tyder på at værdien helst skal ligge under 1 mg P/l (Ejrnæs et al. 2010). Ingen af de målte prøver ligger over denne grænseværdi. Det var altså ikke muligt i marts 2011 at konstatere næringsbelastet overfladevand i nogle af de undersøgte grøfter. Det skal dertil siges at prøverne blev indsamlet efter en tør periode, og ingen af grøfterne bar præg af nogen stor afstrømning.



Figur 3A-C. Oversigt over analyseresultater af vandkemien i området. A=Ammonium (µg/L), B=nitrat (mg/L), C=fosfat (µg/L).

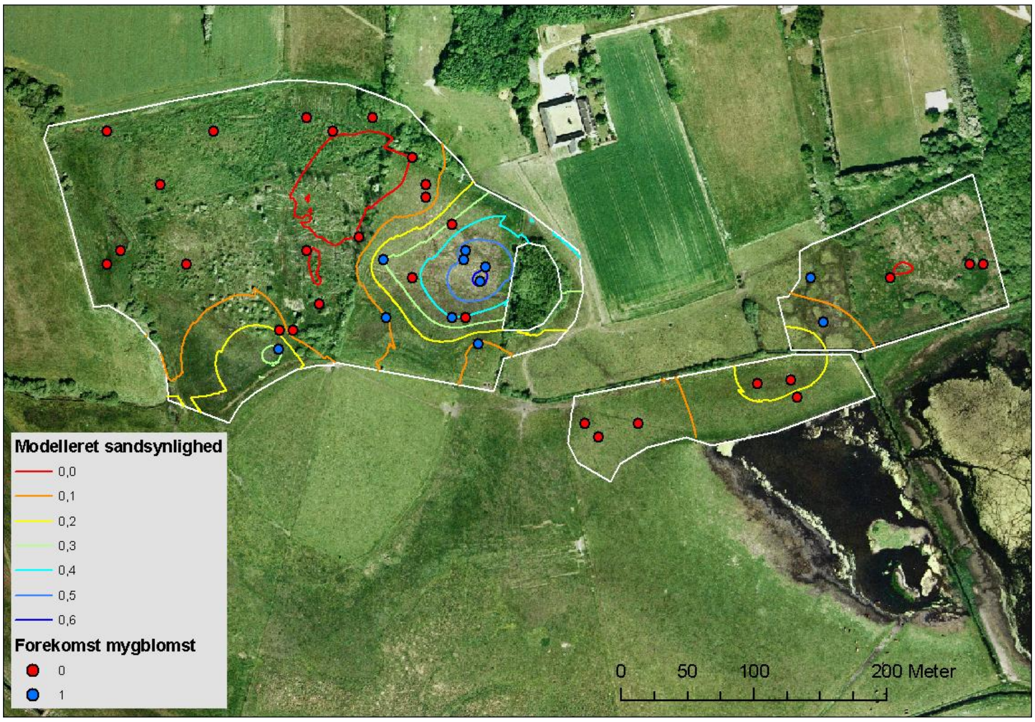
Mygblomst

Mygblomst er fundet i områderne A, B og E med den største og mest stabile bestand i område B. Vi har undersøgt, om det er muligt at forudsige, hvilke områder som er egnet for mygblomst ved at bruge information om vegetationen fra overvågningsfelterne i NOVANA. Til modellen anvendte vi data fra 700 prøvefelter (gentagelser fra forskellige år medtaget) fra seks overvågningsstationer, hvor der har været fundet mygblomst. I modellen har vi forsøgt at forudsige forekomst af mygblomst i prøvefelterne ud fra felternes vegetationshøjde, vedplantedækningsgrad samt en række mål afledt af sammensætningen af plantearter i felterne: Antal typiske rigkærsarter (både mosser og karplanter), Ellenberg-gennemsnit for pH-tal, næringstal, fugtighedstal og ratioen mellem Ellenbergs næring og pH (i det følgende refereret til som næringsratio). Næringsratio har vist sig at være en god indikator for næringsbelastningen i rigkær. Vegetationshøjde og tilgroningsgrad var ikke signifikante, men det var Ellenberg-variablerne samt antallet af typiske arter. Figur 4 viser hvordan sandsynligheden afhænger af næringsratio, fugtighed og pH. Sandsynligheden falder med stigende næringsratio (næringsbelastning), stiger med fugtigheden til et vist punkt, hvorefter den falder, og stiger med stigende pH.



Figur 4. Effekten af næringsratio (nutrat), fugtighed (moist) og pH (ph) på sandsynligheden for at finde mygblomst. De stiplede linjer angiver usikkerhedens størrelse, og usikkerheden afhænger typisk af antallet af observationer, som vises som streger i bunden af figurerne.

Figur 5 viser, hvordan rigkærsområderne indenfor NOVANA-stationen i Helnæs Made egner sig for mygblomst, baseret på modellen for mygblomst på alle NOVANA-stationer. Modellen fra de 6 danske NOVANA-stationer med mygblomst er fint i stand til at forudsige forekomsten i Helnæs Made. Efterfølgende er det undersøgt hvordan forekomsten af mygblomst i Helnæs Made fordeler sig i forhold til koten, beregnet ud fra den detaljerede digitale højdemodel. Sandsynligheden for at finde mygblomst i Helnæs Made er signifikant størst i prøvefelter ved laveste kote. Effekten af kote er stadigvæk signifikant når modellen inkluderer effekten af næringsratio.



Figur 5. Ekstrapolation af forudsigelserne af sandsynligheden for forekomst af mygblomst I Helnæs Made baseret på en model af sandsynligheden vurderet ud fra vegetationens nuværende sammensætning. Prøvefelterne er vist på luftfotoet, og det er angivet i hvilke prøvefelter der er registreret mygblomst under overvågningen.

Forvaltningsforslag

Rigkær og kildevæld er begrænset af forekomsten af kalkrigt, baserigt og næringsfattigt grundvand, som gennemstrømmer tørven. Hydrologisk genopretning vil derfor i første omgang være målrettet, at grundvandet ikke ledes bort fra kæret via grøfter, men siver langsomt gennem kærområdet ved at følge terrænets naturlige fald. Det er blandt andet hollændernes erfaring, at det ofte er mere perspektivrigt at undgå afledning af grundvandet i selve kærområdet end at regulere vandindvinding eller arealanvendelse i oplandet, selvom dette også kan være påkrævet.

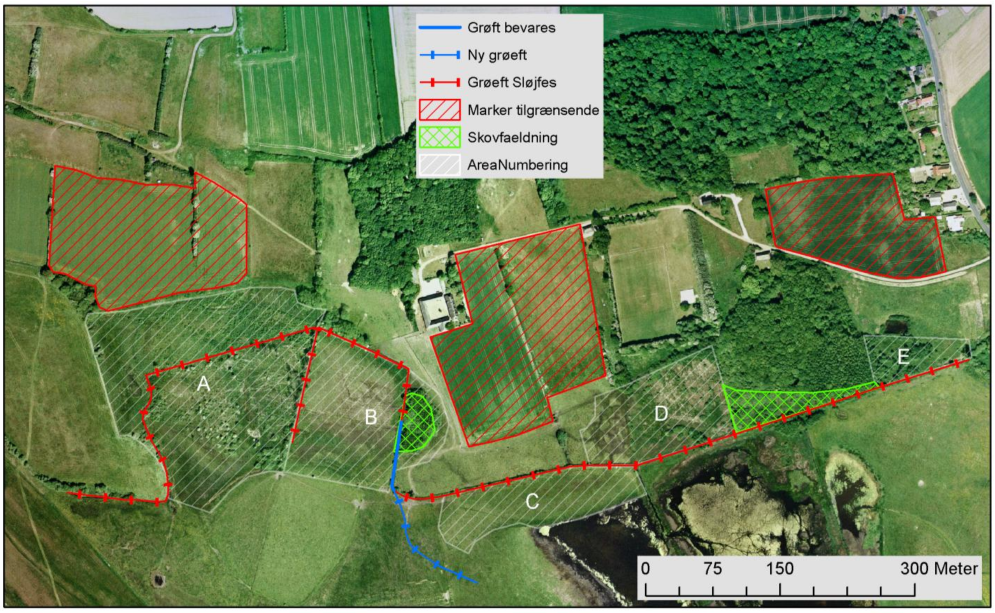
Hvis man kigger på oplandet til rigkærene i mygblomstområdet, så er det ikke stort sammenlignet med mange andre udstrømningsområder, simpelthen pga. øens størrelse. Bedømt ud fra oplandets topografi er det næppe større end 35 ha. Arealet af rigkærene er 10 ha. Der dannes maksimalt 1 mm grundvand pr. dag i oplandet – hvilket bliver til 3,5 mm pr. dag hvis alt vandet kommer gennem rigkærene. Realistisk set er det nok kun 1-2 mm pr. dag, der i gennemsnit kan forventes at strømme til rigkærene. Til sammenligning fordamper der ca. 5 mm pr. dag på en varm sommerdag. Altså har vi med et område at gøre, hvor grundvandstilførslen er i den lave ende – eller i hvert fald ikke ligefrem springer frem af skrænten. Derfor er der særlig grund til opmærksomhed for at undgå, at grundvandet ledes udenom rigkæret via drængrøfter.

På den anden side er det også vigtigt at sikre, at grundvand og regnvand kan sive gennem og ud af rigkærsområdet i perioder med overskydende vand. Den eneste passage ud af området A og B er via den lille lavning i det sydlige hjørne af område B, hvorfra vandet kan passere med terrænet til Åledyb.

Udover ovenstående overvejelser, er projektforslaget baseret på, at vandet i drængrøfterne gennem og omkring rigkærene ikke var mærkbart belastet af næringsstoffer under prøvetagningen i marts 2011.

Figur 6 viser forslaget til hydrologisk genopretning af rigkærene. Vi foreslår følgende:

1. Lukning af de interne og omkringliggende grøfter i rigkærsområderne.
2. Fældning af vedplanter omkring grøfterne
3. Grøfterne kan med fordel kastes til med materiale fra afskrabning af det øverste tørvelag omkring grøfterne, hvorved koten kan bringes i niveau med mygblomstområderne.
4. Etablering af en kompenserende lav grøft eller grøblerende, etableret fra det sydlige hjørne af område B i retning mod Åledybet.
5. Sikring af områdets græsning ved en helårsgræsning med lette og robuste kvægracer, som kan færdes i rigkæret.



Figur 6. Projektforslag med skitsering af grøfter som foreslås tilkastet (rød) og grøft/grøblerende som foreslås etableret. Endvidere er markeret to områder med potentielt rigkær, som foreslås ryddet for vedplanter. Endelig er marker hvorfra der kunne forekomme næringsstofudvaskning til rigkærsområderne markeret med rød skravering.

I praksis kan projektforslaget med fordel gennemføres etapevis, ved start i område A, efterfulgt af E, C+D og endelig B, og med monitering af effekterne på områdets hydrologi og vegetation.

Det ville være hensigtsmæssigt at gennemføre en forundersøgelse af vandgennemstrømning og vandkemi i de grøfter, som planlægges afbrudt med henblik på at forudsige effekterne på områdets hydrologi. Tilsvarende ville det være hensigtsmæssigt at undersøge risikoen for overfladisk eller drænført afstrømning og deraf følgende næringsstofbelastning fra tilgrænsende marker til rigkærsområderne. I givet fald vil det være nødvendigt at håndtere denne forureningskilde – enten ved udlæg af udyrkede bufferarealer, eller ved opsamling af drænvand i et konstrueret vådområde. Skovrejsning eller fri succession vil give en effektiv tilbageholdelse af næringsstoffer, men udyrkede græsarealer (overdrevssuccession) vil give tillige give en større infiltrering af regnvand til grundvandsmagasinerne.

Det anbefales ikke at hæve vandstanden i Helnæs Made yderligere ved ændret pumpning, da dette kan forårsage stuvning af overfladevand, og forværring af bevaringsstatus for områdets rigkær.

Det nordlige rigkær

Mod nord ligger et ganske lille rigkærsområde, som afvandes ved en lav grøblerende. Rigkæret forekom tørt ved besigtigelsen i marts 2011, og det foreslås at tilkaste grøblerenden for at stoppe afvandingen af området.

Det sydlige rigkær

Mod syd forekommer et lidt større rigkærsområde. Området forekom vådt under besigtigelsen i marts 2011, og med mere stagnerende vandstand end rigkærene ved Åledyb. Vandstanden i området svinger muligvis mere end ved Åledyb, og i så fald kunne man med fordel tilkaste områdets grøblerender uden at rigkæret bliver for vådt til sommergræsning.

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APPENDIX IV

VANDSTAND OG NATURKVALITET HÆNGER SAMMEN

English title: Water level and habitat quality are linked
Full size PDF file can be downloaded from:
http://vbn.aau.dk/files/42682997/Vandstand_og_naturkvalitet_i_rigk_r_h_nger_sammen.pdf

English summary:

The poster presents preliminary analyses on the data on which *Paper III* was based. The water level response to a dry summer period in 2008 was related to the species composition at 12 different fen locations in Denmark. Water level is shown to be significantly correlated to the Ellenberg moisture and nutrient scores.

Poster presented at the annual freshwater symposium (Ferskvandssymposiet) 2-3 March, 2010 held in Roskilde. Arranged by Department of Bioscience, Aarhus University, Denmark

VANDSTAND OG NATURKVALITET I RIGKÆR HÆNGER SAMMEN

Introduktion

23 vandstandstidsserier fra 12 forskellige rigkærs-områder i Jylland og på Fyn er blevet analyseret med det formål at etablere et link mellem målbare hydrologiske karakteristika og vegetationssammensætningen på lokaliteterne.

Kontinuerte registreringer af vandstanden sikrer at områdernes tidsvarierende respons på nedbør, fordampning og vandtilstrømning opfanges.

Ellenbergs plante-indikatorer for fugt, næring og pH anvendes ofte til at udlede naturtypens preferencer og i forbindelse med vurdering af naturtilstanden. Det er forventningen, at vandstandsvariationerne afspejles direkte i Ellenberg fugt værdierne, men også at næringsbelastning og pH-værdi indirekte påvirkes af hydrologien.

Målet er, at resultaterne på sigt vil kunne understøtte beslutninger, som omhandler hydrologiske påvirkninger af naturtypen, samt anvendes i forbindelse med naturgenopretningsprojekter.

Metoder

Datagrundlag

Vandstandsdataene, som er analyseret, stammer dels fra miljøcentrenes indrapportering til fagdatacenteret, dels fra et tværgående økohydrologiprojekt under NOVANA og dels fra et PhD projekt på Aalborg Universitet. Vandstanden er registreret på time til døgn basis.

For hver vandstandsstation er den nærmeste artsregistrering med tilhørende ellenberg værdier udtrukket fra NOVANA og DEVANO programmerne.

Vegetationsafledte indikatorer

Nye undersøgelser viser, at Ellenberg-fugt er tæt relateret til forekomsten af de sejlkrummede mosarter, som er specialiserede til de konstant vandmættede forhold og typisk er sårbare overfor både udtørring og eutrofiering.
[Andersen, Dagmar 2009, præsentation "Hydrologi og næringsstoftilgængelighed i kildevæld og rigkær"]

Næringsratio (Ellenberg N/ Ellenberg R) anvendes internationalt som en robust indikator for naturtilstanden i rigkærsområderne. I denne analyse har det imidlertid ikke være muligt at finde en signifikant sammenhæng mellem vandstandsdataene og indikatoren næringsratio. Derimod har Ellenberg N/ Ellenberg F vist sig at korrelere med den målbare hydrologi og er samtidigt et godt mål for naturtilstanden i naturtypen rigkær baseret på artsscoresystemet [Faglig rapport fra DMU nr.735. 2009].

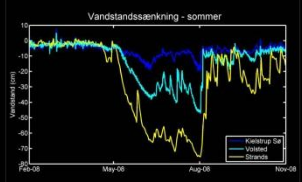
Analyse af vandstandsdata

Der er udvalgt en periode i dataene,1. maj - 31 juli 2008, hvor der har været en længerevarende landsdækkende tørkeperiode, som har haft indvirkning på vandstanden ved alle måle-stationer. For denne periode er spredningen i form af den interkvartile afstand (IQR) brugt som mål for udtørringen. Den maksimale sænkning i perioden er også afprøvet og giver en mindre signifikant sammenhæng.

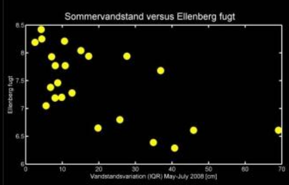
Ved at anvende et statistisk mål for spredningen frem for f.eks. afstanden mellem terræn og vandspejl undgås usikkerheder ved indmåling af pejlerør og den i mange tilfælde uklare definition på terrænets niveau.

Resultater

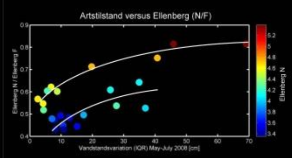
Vandstandsdata fra rigkærslokaliteterne viser generelt en stabil og terræn-nær vandstand i efterår, vinter og tidlige forårsperioder. Der er imidlertid stor forskel på responsen på tørre sommer-perioder. Her er 3 eksempler vist.



Figuren viser sammenhængen mellem den målte vandstand og den vegetationsafledte fugt indikator. Vegetationen afspejler en signifikant (Spearman p=0.003) større fugtighed på lokaliteter, hvor vandstanden er stabil i tørre perioder.



Forholdet mellem Ellenberg N og Ellenberg F er den vegetationsbaserede indikator, som i undersøgelserne bedst har kunnet relateres til vandstandsvariationerne, og som samtidig kan anvendes som indikator for naturkvaliteten. Figuren indikerer en opdeling mellem de eutrofierede (gule-røde) og de mere næringsfattige (blå-grøn) lokaliteter.



Konklusion

Rigkær er komplekse økologiske systemer, hvor naturkvaliteten afhænger af et samspil mellem flere korrelerede variable, og hvor de forskellige faktorer ikke umiddelbart kan adskilles fra hinanden. Ikke desto mindre ses det som en nødvendighed, at finde frem til robuste parametre, som kan måles i felten og som korrelerer med naturkvaliteten. Datagrundlaget i undersøgelserne er endnu sparsomt, men vil blive mere omfattende i den kommende tid i takt med indrapporteringen fra de enkelte Miljøcentre.

Undersøgelserne viser, at Ellenberg værdierne for fugt samt forholdet mellem næring og fugt (N/F) afspejler vandstandsdataene, som er indsamlet i rigkærene.

Det forventes, at en styrkelse af datagrundlaget og en udvikling af en målrettet indikator for naturtilstanden i rigkær baseret på typiske arter for naturtypen, vil medføre en mere entydig og praktisk anvendelig sammenhæng mellem hydrologi og økologi.

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AALBORG UNIVERSITET

APPENDIX V

MODELLING HYDROLOGICAL CONSEQUENCES ON GROUND-WATER DEPENDENT HABITATS

Full size PDF file can be downloaded from:
http://vbn.aau.dk/files/55707635/Modelling_Hydrological_Consequenses_on_Groundwater_Dependent_Habitats.pdf

Presented at the 2010 Latsis Symposium, 17-20 October 2010, Lausanne, Switzerland

Organized by EPFL (École Polytechnique Fédérale de Lausanne)

Modelling hydrological consequenses on groundwater dependent habitats

Aalborg University

Introduction

A well field is planned 1 km north of a Danish river valley which is covered by a NATURA 2000 habitat area. Fens and springs in the area depend on stable groundwater flows and the well field potentially threatens the integrity of the habitats.

Hydrological modelling is potentially a very useful tool for studying how different abstraction scenarios affect the hydrology in the habitats. However it is necessary to describe groundwater, vadose zone and surface water flows on a small scale to capture the important flow processes. This is on the edge of how far we can go with distributed modelling today and requires a large amount of input, calibration and validation data.

In the presented work a solid data foundation for hydrological modelling was provided by intensively monitoring the natural hydrological conditions during a 3-year period and subsequently performing pumping tests and monitoring effects of pumping from the groundwater aquifer.

Hydrological modelling is shown to be a very useful tool for supporting decisions regarding groundwater abstraction in catchments that contain groundwater dependent nature.

Nested hydrological models

The model is a 3D distributed model describing saturated flow, unsaturated flow as well as surface runoff. A regional groundwater model is used to provide the boundary conditions for submodel 1 with a resolution of 25 X 25 meter and a detailed model for the fen area of 5 X 5 meter resolution.

The nested modelling approach is used to achieve a sufficient resolution and yet a manageable computational demand in the models.

Figure 1: Boundary for the nested hydrological models

Small scale hydrology in fens

The rich fen area is located in a small depression in the terrain as illustrated in figure 2. Surface runoff in the fen ensures that flooding does not occur and the drainage ditches transport the water to the river. The model result is highly sensitive towards the detailed topography and the level of ditches and spring-overflows in the area. The 5 X 5 metre horizontal resolution is required to resolve these small scale structures in the numerical model.

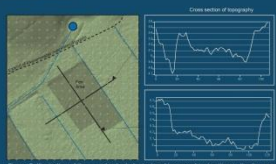
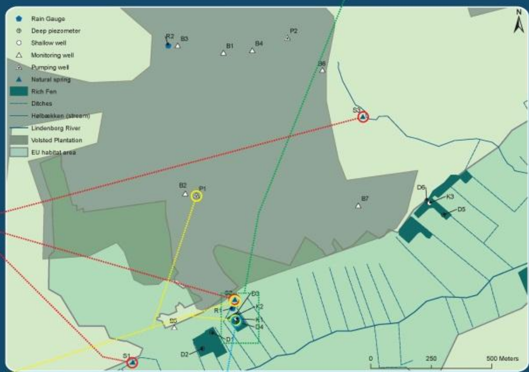


Figure 2: Illustration of the complex hydrological and topographical setting in the fen area



Modelling flow in natural springs

The flow in the springs play an important role in the ground-water surfacewater interaction in the rivervalley. Springflow is believed to be a result of cracks and highly conductive path-ways in the limestone aquifer. The actual structure and ex-tend of these pathways is unknown.

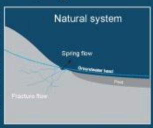


Figure 3: The perception of springflow in natural spings in study area

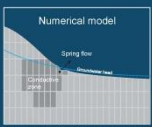


Figure 4: Principle of spring flow i the numerical model

In the numerical model a highly conductive zone con-nects the aquifer to a drain cell with a level correspon-ding to the water table in the spring. The leakage coeffi-cient in the drain cell is high allowing water to flow freely.

Model validation

Figure 5:
Modelled and observed spring flow (S2) during pumping test i the well p1. The model response is slower than the actual response due to dual porosity in the limestone aquifer, but the simulated flow reduction matches the mea-surementes

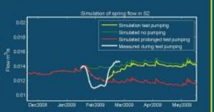


Figure 6:
Modelled and observed head elevation in a short (upper graph) and a deap (lower graph) piezometer in the fen area.
The model gives a good description of the water level fluctuations in the rootzone of the plants during both winter and summer periods.

Effect on head elevation and discharge through fens

The graphs illustrate the simulated impact on the fen from a realistic abstraction scenario starting on January 1st 2008. In dry periods during the summer the evapotrans-piration exeeds the ground-water discharge to the area and the water table drops as a part of the naturally occuring variations. The abstraction increases this drawdown by 3 cm (fig. 7).

During the winter season the watertable in the fen is not affected, but instead the groundwater discharge through the system is reduced by 10-25 % (fig. 8)

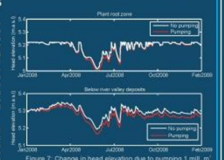


Figure 7: Change in head elevation due to pumping 1 mill. m^3 pr. year from the plantation

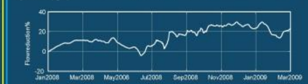


Figure 8: Reduction in groundwater discharge to the fen area due to pumping of 1 mill. m^3 pr. year from the plantation

Conclusion

The hydrological effect of groundwater abstraction on groundwater dependent habitats has been quantified by combining integrated numerical models at different scale. The model depends on a large amount of input data and observations used in calibration of parameters. The results can to some extent be validated and confirmed by measurements in the natural springs during pumping tests. In the fen areas no significant effect of pumping was measured and the reliability of the model depend on the ability to reproduce natural variations in the water level.

A scenario where 1 mill. m^3 of water is abstracted from the plantation north of the river valley was simulated. The modelling results indicate that the water level in the rootzone of the fen will be lowered a few centimetres (fig. 7) during the summer period which is not considered critical. It is likely to be more important that the groundwater flow to the fen will be reduced between 10 % and 25 % according to the simulations (fig. 8).

Using hydrological modelling tools for prediction in groundwater dependent habitats gives not only the possibilities of conducting risk assessments and evaluating different abstraction scenarios, but it also contributes to the understanding of the hydrology that controls these areas. Potentially models are very useful in any habitat restoration project that involves changes to the hydrological regime however very large datasets are required.

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Aalborg Utility Company and NIRAS A/S have conducted a large part of the investigations at the site.

Aalborg Utility Company
NIRAS
FONDATION LATSIS Internationale

APPENDIX VI

HEAT AS A TRACER TO DETERMINE GROUNDWATER SEEPAGE IN WETLANDS

Possibilities of using heat as a tracer of vertical groundwater movement in discharge wetlands were investigated. In river and lakes temperature has been successfully applied for quantification of vertical fluxes for a few decades since a method was introduced by (Lapham 1989). In this appendix the theory behind one-dimensional heat transport in a porous saturated media is described. A sensitivity analysis is made illustrating the theoretical influence of seepage on temperatures in the sub-surface of a wetland. Two ideas have been tested by field measurements and a brief discussion the results and the applicability is presented. The work has not been published.

Theory

One-dimensional transport of heat in a porous media can be described analogous to solute transport by the advection dispersion equation (ADE).

$$\frac{\partial \tau}{\partial t} = D\nabla^2\tau - v\nabla\tau$$

where
τ is the concentration of a solute [kg m^{-3}]
t is time [s]
v is the velocity of water which is assumed constant in space and time for this application [m s^{-1}]
∇ denotes the first derivative with respect to the independent spatial variable e.g. $(\frac{\partial}{\partial z})$
∇^2 denotes the second derivative with respect to the independent spatial variable e.g. $(\frac{\partial^2}{\partial z^2})$

Heat transport can be formulated by the similar mathematical expression, here adapted from (Anderson 2005)

$$\frac{\partial T}{\partial t} = \frac{k_e}{\rho c}\nabla^2 T - \frac{\rho_w c_w}{\rho c}\nabla(Tq)$$

where
T is the temperature [^{o}C]
ρ is the density of the water-soil matrix [kg m^{-3}]
ρ_w is the density of water [kg m^{-3}]
c is the specific heat of the water-soil matrix [J/kg/ ^{o}C]

c_w is the specific heat of water [J/kg/ ^{o}C]

q is the seepage velocity (Darcy velocity) [m s^{-1}]
k_e is a term that includes the effective thermal conductivity of the water-soil matrix and heat dispersion due to velocity gradients [W/(m ºC]

k_e can be explained by the following relationship (Anderson 2005):

$$\eta = \frac{k_e}{\rho c} = \frac{k_o}{\rho c} + \alpha |q|$$

where
k_o is the effective thermal conductivity [W/(m ºC]
$k_o/\rho c$ is analogous to the diffusion coefficient in the ADE [m^2/s]
α is dispersivity analogous to the dispersivity of a solute [m]
q is the seepage rate [m/s] equal to the velocity of water multiplied by the total porosity

The effective thermal conductivity is calculated by (Anderson 2005):

$$k_o = nk_w + (1-n)k_g$$

where
n is the porosity [-]
k_w: Thermal conductivity of water [W/(m ºC]
k_g: Thermal conductivity of the soil matrix [W/(m ºC]

Heat capacity can be calculated similarly by (Anderson 2005) :

$$\rho c = n(\rho_w c_w) + (1-n)\rho_g c_g$$

Temperature sensitivity towards groundwater seepage

In order to illustrate the sensitivity of heat transport to varying seepage velocities the one-dimensional heat equation for a porous media was solved. A numerical solution was preferred within this study to allow flexibility in boundary conditions and variations in soil parameters with depth. An implicit Crank Nicolson solution scheme was applied (Crank and Nicolson 1996) which is known to be stable and produce relatively small numerical errors depending on the discretisation. All parameters used for this sensitivity analysis are listed in Table 2.

Table 2. Parameter values for sensitivity of heat transport against seepage rates

Symbol	Parameter	Value	Comment
q	Seepage rate	-9 to 20 mm day^{-1}	varied
K_w	Thermal conductivity of water	0.6 W m^{-1} ºC^{-1}	fixed
K_g	Thermal conductivity of soil grains	0.4 W m^{-1} ºC^{-1}	calibrated in (McKenzie et al. 2007)
C_w	Specific heat capacity of water	4182 J kg^{-1} ºC^{-1}	fixed

C_g	Specific heat capacity of peat	3500 J kg^{-1} °C^{-1}	calibrated in (McKenzie et al. 2007)
ρ_w	Density of water	1000 kg m^{-3}	fixed
ρ_g	Density of soil	850 kg m^{-3}	(McKenzie et al. 2007)
α	Thermal dispersivity	0 m	Dispersion assumed negligible compared to conduction
n	Porosity	0.5	fixed
dt	time step	1 h	
dz	spatial discretisation	0.1 m	

Fig. 10 shows the effect of groundwater seepage on the annual temperature range (difference between highest and lowest temperature) for different depths below the surface. The sensitivity is represented by the slope of the lines in the figure. The upper boundary in this example follows a sinusoidal curve with a mean value of 8.0 °C and amplitude of 8 °C. Groundwater temperature at a depth of 10 m is assumed constant at 8 °C. The largest modelled effect on the annual temperature range is approximately 2 °C per 5 mm day^{-1} of seepage. Seepage rates between 0 and 5 mm day^{-1} are expected to be common in discharge wetlands and within this interval the annual temperature range changes less than 1.5 °C per 5 mm day^{-1} of seepage.

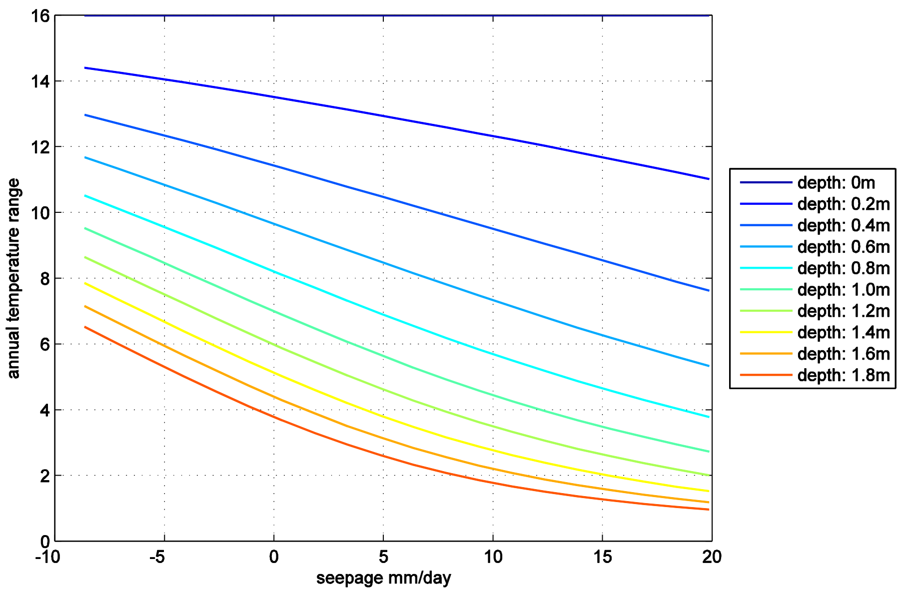

Fig. 10. Illustration of the annual temperature range as function of seepage rate for different depths below surface. Seepage is positive for upward flow (exfiltration) and negative for downward flow (infiltration)

Fig. 11 illustrates the temperature variations due to daily fluctuations. At the surface daily temperature fluctuations are here assumed to be sinusoidal with amplitude of 5 °C. The seepage rate has very little impact on the diurnal fluctuations and below 40 cm depth the daily temperature variations are smaller than 1 °C.

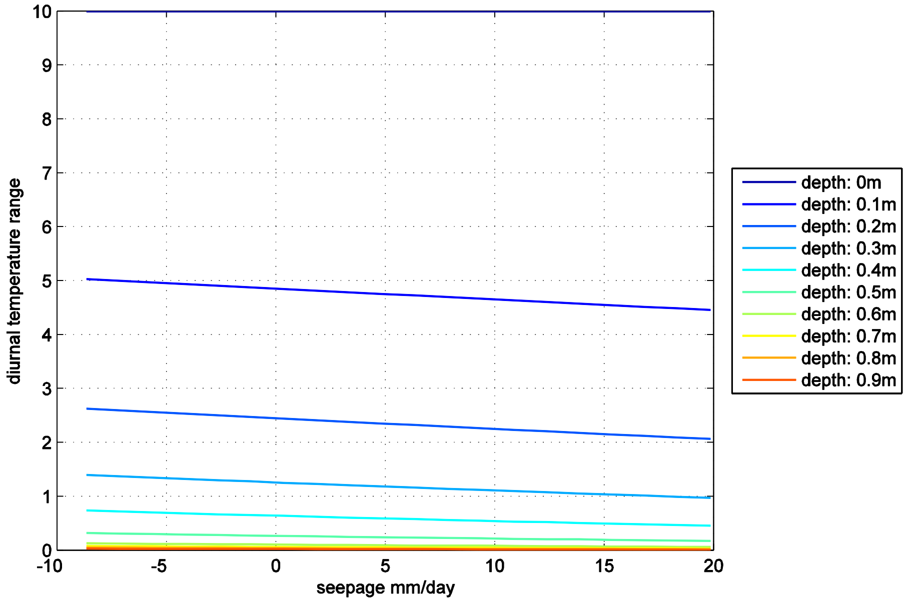

Fig. 11. Illustration of the diurnal temperature range as function of seepage rate for different depths below surface. Seepage is positive for upward flow (exfiltration) and negative for downward flow (infiltration)

It seems clear from this sensitivity analysis that the overall the sensitivity of temperature towards vertical seepage is low. The largest sensitivity can be expected at depths between 0.5 and 1.5 m below ground where the fluctuations near the surface have little effect. It is also clear, that the assumptions regarding strictly vertical water flow and heat transport as well as heat transfer between the upper soil and the atmosphere must be true or at least comparable between measurement points for clear seepage patterns to be obtained. This small sensitivity study has not included any uncertainties in parameter values.

The examined ideas

Two ideas were examined and brief descriptions and preliminary results are presented below. The first idea was too use temperature profiles to map spatial variations in groundwater seepage in river valleys. The expectation was that a large number of profiles conducted within a short period of time would be sufficient to reveal patterns of high and low discharge zones. Initial tests were during May to July 2008 in a fen area near Volsted Plantation located in the Lindenborg river valley. Temperature profiles were constructed with six measurements in the upper 60 cm of the peat profile. For this purpose a temperature spear was constructed and six thermocouples (tolerance of +- 0.15 °C) were attached. The measurement points were selected with the aim of representing both areas high and low seepage rates. The highest seepage rate was expected in the profile named *K2* while small seepage rates where expected at *D5* and *om1*. These expectations are supported by the vegetation composition, water level data and the visual impression from field investigations. The temperature profiles (Fig. 12) showed very low temperatures at *om1* indicating high seepage opposite to what was expected. At o*m1* the upper part of the soil profile (10-20 cm) is unsaturated. At *K2* a high seepage rate was expected while an intermediate temperature profile was measured. Here the profile was fully saturated and some areas of bare soil (no vegetation) were present. According to the sensitivity analysis we expected temperatures near the surface to be fairly indifferent for profiles located in the same area, but we observed differences in the range from 12.7 to 15.3 at a depth of 10 cm. These temperature differences observed near the surface seem to be almost constant with depth.

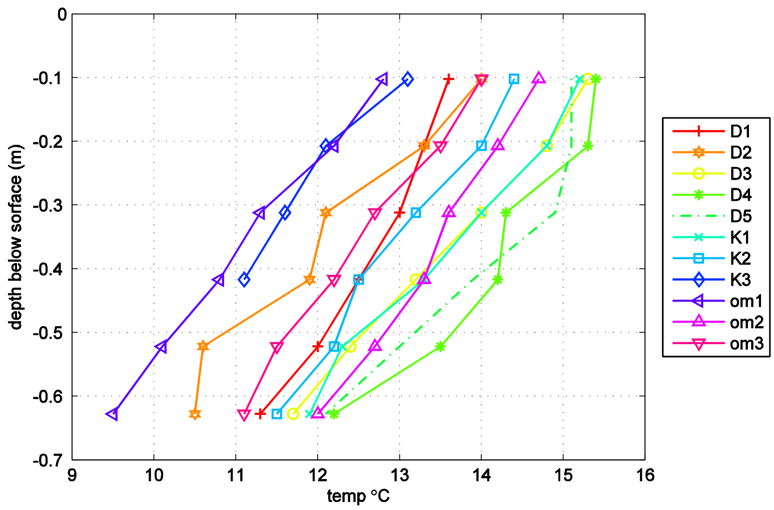

Fig. 12. Temperature profiles measured in a fen habitat on 2 July 2008 during a two hour period between 12:00 and 14:00. Air temperature 20-25 °C

The second idea was to use time series of temperature recorded by loggers placed inside piezometers. Many of the pressure transducers used in wetland monitoring programmes also measure temperature, and therefore potentially many useful time series exist already. By assuming that the water temperature inside the piezometers is in equilibrium with temperatures in the soil, these data might reflect seepage rates. Only one logger has been placed in each piezometer, hence no information on variation at the surface or with depth was obtained in this approach. However, if surface temperature can be assumed to follow the air temperature and deep groundwater temperature is constant then the heat transport problem can be solved. Fig. 13 shows temperature variations in piezometers at depths between 0.5 and 0.9 m below ground. Most of the time series show a constant annual variability whereas K3 seem to behave differently. The measured temperature was here low both during summer and winter periods and the annual variability was smaller in 2007 than in 2009 and 2010.

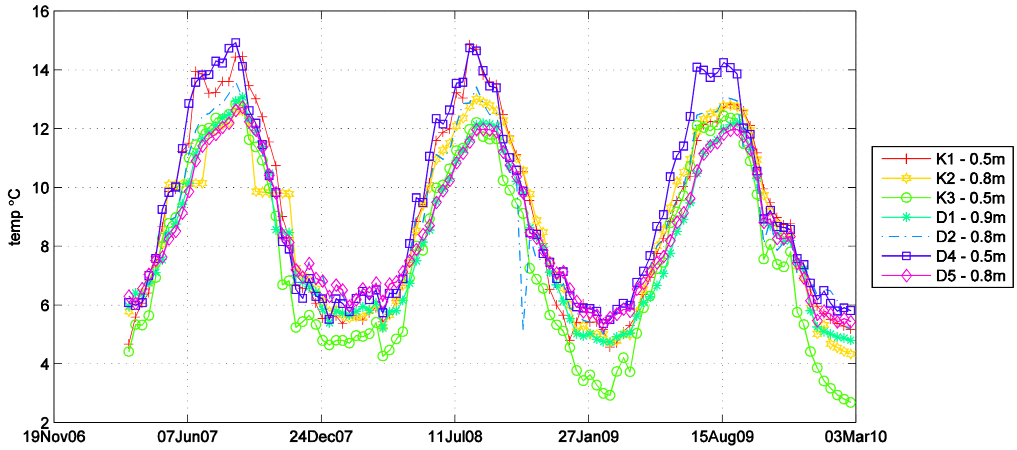

Fig. 13. Temperature variability in piezometers during a three year period

Table 3 summarises the results obtained from the time series and by applying the curves on Fig. 10 the seepage rates were estimated. Seepage rates in the range between 1 and 7 mm day^{-1} were obtained, and this seems reasonable. However the temperatures in *K2* again indicate a small seepage which contradicts strongly with the expectations.

Table 3. Seepage rate determined from temperature time series in Fig. 13 by using the diagram shown in Fig. 10.

Piezometer	Depth (m)	Annual variability (°C)	Seepage (mm day^{-1})
K1	0.53	9.0	7
K2	0.77	8.0	1
K3	0.49	9.0	7
D1	0.88	7.0	2
D2	0.76	7.5	2
D4	0.53	9.0	7
D5	0.77	7.0	4

Discussion

It was found, that temperature profiles in the upper 60 cm of the soil varied much spatially and that these variations were not related to differences in seepage, but rather heterogeneity at the soil surface. Annual temperature variability measured in piezometers could be useful for rough seepage estimates; however, differences in vegetation cover strongly affect the results.

The assumptions for using the heat equation to determine seepage rates in discharge wetlands are many. The most important in this study is related to the upper boundary condition. The presented examples indicate that heat fluxes at the soil surface may differ dramatically depending on vegetation cover and absorption of radiation from the sun, and this is believed to be the most important source of error.

The problem of solving the energy balance near the soil surface has been widely explored and is closely related to the determination of evapotranspiration. Hence it may be possible to unravel these sources of uncertainty. However the purpose of using temperature to indicate seepage rates was to achieve a robust estimate that did not involve detailed investigation of parameters with large spatial variability. If this problem require, that soil properties and vegetation cover is firmly described then the idea does not provide any shortcut. It is possible that a simple classification would provide enough consistency for the method to be relevant in groundwater dependent wetlands.

Others have used profiles of temperature envelopes (maximum – minimum temperature) in wetlands to determine seepage. {{20 Hunt,R.J. 1996}} used 3-4 thermocouples in each profile and the upper and lower measurements were used as boundary conditions for solving the model proposed by Lapham (1989). Thereby {{20 Hunt,R.J. 1996}} did not depend on assumptions regarding air temperatures and surface heat exchange. Nonetheless they estimated uncertainties on the obtained seepage rates to be approximately +- 5 mm day^{-1}. Seepage rates in fens are expected to be in the order of 0-10 mm day^{-1}. Based on these preliminary results and the work of others it was not trusted that temperature modelling would provide accurate results in the context of this study.

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Part 3 Scientific papers

PAPER I

EFFECT OF GROUNDWATER ABSTRACTION ON FEN ECOSYSTEMS

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PAPER II

QUANTIFICATION OF SEEPAGE IN GROUNDWATER DEPENDENT WETLANDS

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Submitted to Journal of Hydrology March 2011

PAPER III

RELATIONS BETWEEN VEGETATION AND WATER LEVEL IN FENS

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PAPER IV

From groundwater abstraction to vegetative response in fen ecosystems

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