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Modelling to support the assessment of interlinkages between groundwater and surface water in the context of the EU Water Framework Directive

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Abstract The EU Water Framework Directive (WFD) includes new common standards for an integrated assessment of entire hydrological systems at the catchment scale, implying among others, that water abstraction may not affect dependent ecosystems such as wetlands, lakes and water courses, nor the water quality of existing drinking water resources. Methods are needed to ensure that these requirements are fulfilled. To this end we developed and tested a procedure based on the application of results from a regional groundwater model for the whole county of Funen (Denmark) to investigate linkages between groundwater bodies (GWBs) and surface water, both under current and pristine conditions with respect to groundwater withdrawal. We found that discharge areas derived from the model application provide a good estimate for areas where GWB potentially may contribute to river runoff. For each GWB located at least partly within these areas, investigations have been performed whether or not hydraulic heads within some parts of the respective GWB are high enough to assume a contribution to river discharge. Additionally, median values of series of annual minima of daily river discharge measured at various locations along the main water courses in Funen County have been included in the investigations of groundwater/surface water interaction. The approaches applied are useful and repeatable for the regional basis analysis of the WFD, but require improvements, as discussed in the paper.

Key words water framework directive; groundwater–surface water interaction

BACKGROUND AND OBJECTIVES

In Denmark, numerical groundwater models have been used during recent years to assess conditions for drinking water abstraction from groundwater bodies (GWB) at the local to regional scale within the frame of groundwater management action plans. More recently, the regional water authorities in Europe are obliged to assess all components of the hydrological catchments systems in line with the implementation of the European Union Water Framework Directive (WFD). Interlinkages between groundwater and surface water bodies are ecologically important in a multiple way and both directions (Sophocleous, 2002) and operational tools to estimate the interlinkages are highly required for WFD analyses (Procter *et al.*, 2006). Hydrological modelling systems integrating both surface and subsurface components, structures and processes of the hydrological cycle may be helpful to perform catchment analyses that not only focus on the elements in a separate way, but rather enable investigation of interdependencies between them (Højberg *et al.*, 2007).

As part of the implementation of the WFD the Danish environmental protection agency initiated a project to classify groundwater bodies with respect to surface water contacts (Dahl *et al.*, 2004, 2005) to enable investigations whether or not the GWBs comply with the quality criteria stipulated in the directive, i.e. dependent adjacent surface water bodies are not to be prevented from achieving their environmental goals. Abstraction from GWB must not cause the status of the neighbouring areas to be deteriorated, or cause significant damage to the terrestrial ecosystems that depend directly upon the groundwater reservoir. Concepts developed as parts of the project have been implemented into the Danish guidelines for the characterisation of groundwater bodies. Our paper is mainly focused upon the related subdivision of aquifers into shallow, regional and deep GWBs, which may be linked to surface water bodies seasonally, perennially or never, respectively.

One of the main areas to test and perform the implementation of the WFD in Europe is the Odense Fjord River basin being located in the former county of Funen. The county was among the first regional authorities in Denmark to systematically use conceptual geological models and groundwater models for decision making. Within the WFD pilot river basin (PRB) study for the Odense Fjord catchment as well as for the WFD reporting, we decided to apply the regional groundwater model for the whole county of Funen for investigating linkages between GWBs and surface water both under pristine and current conditions with respect to drinking water abstraction. The main objective of the paper is to present newly established model-aided methods for the identification of linkages between groundwater and surface water, including both geographical location and direction (from groundwater to surface water or *vice versa*), which can be used on the regional scale to assess catchment water pathways and areas with impacts from over-abstraction of groundwater.

Though the paper focuses on surface water interaction, the modelling results can similarly be used when focusing on areas with possible abstraction impact on the water quality of the GWB (Mielby, 2006).

MATERIAL AND METHODS

The MIKE SHE type of model we applied consists of nine vertical layers, has a spatial resolution of 1 km^2 and covers the area of the entire county, i.e. approx. 3500 km^2 (Henriksen *et al.*, 2003). Simulation runs with daily time steps have been performed with a calibrated and validated set-up for the period of 11 years from 1990 to 2000 with current climatic conditions as input. The Danish guidelines for the characterisation of groundwater bodies require pristine conditions to be applied for analyses, which imply, in terms of groundwater management, that no abstraction may occur. Calibrated simulation models integrating all components of the hydrological cycle are hence the most well suited tools to perform analyses for these hypothetical or historical conditions. When applying these pristine assumptions with no water abstractions to occur to the models, the location of areas showing upward oriented hydraulic gradients in the groundwater model show good correlation to the combined location of lowland soils according to maps drawn in 1890 (Fig. 1), and the current distribution of wetland soils and surface information on the location of both spots and areas where groundwater discharge to terrain surfaces has been measured. Of the total number of 1920 cells, 1750 (91%) with upward-oriented gradients intersect with polygons on either the old lowlands soil or the wetland soils. Due to the good correlation found, discharge areas derived from the model application have been assumed to provide a good estimate for areas where GWB may potentially contribute to river runoff and *vice versa*.

The Funen County database on GWB comprises information on 123 units varying in size between 0.12 and 266 km^2. For each of the units located at least partly within these modelled discharge areas, investigations have been performed whether or not hydraulic head within some parts of the respective GWB is high enough to assume potential contribution to river discharge. To fulfil this criterion at least parts of GWB surface elevations, where adjacent river and wetland ecosystems are located, have to be lower than 1 m above the potentiometric surface, as the average depths of the lowland brooks dominating the water courses on Funen was estimated to 1 m. The possible error introduced by applying this assumption will be smaller than uncertainty related to the horizontal resolution of the model applied. The potentiometric heads have been identified separately for each aquifer layer in the groundwater model to account for the specific vertical location of the respective GWB within the geological model used for the MIKE SHE application.

As an additional independent source of information, median values of series of annual minima of daily river discharge (MMRD) measured at various locations along the main water courses in Funen County have been included. MMRD are a rather common measure in Denmark to describe low river flow conditions and are used as an independent estimate of groundwater discharge to river runoff. As part of the work performed by Dahl *et al.* (2005) a tool was developed to relate MMRD values from 556 stations, available for the whole of Funen, to main river reaches. The low-flow statistics are based on data gathered between 1976 and 1991. The tool calculates downstream changes in lowflow, which enables the user to estimate whether differences in contribution of groundwater discharge to river flow at a specific river reach is positive, unchanged or negative. Regional GWBs can be characterised by significant positive or negative downstream changes in

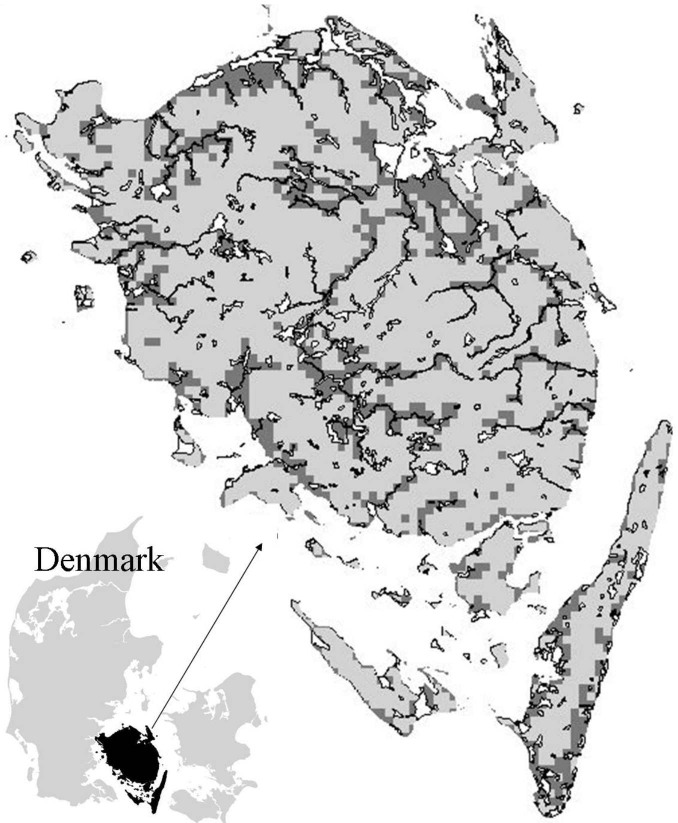

Fig. 1 Map showing lowland soils mapped in 1890 (black) and areas with upward oriented gradients in potentiometric heads (dark grey) for the entire county of Funen when no groundwater abstraction occurs.

MMRD along the adjacent river reach, while no changes in MMRD can be observed for deep GWBs, which by definition lack linkage to surface water ecosystems. In catchments where only shallow GWBs exist, no low flow can be observed during parts of the year, implying that MMRD equals zero (Danish EPA, 2004). Finally, scenario model runs have been performed that differ from the zero scenario (no abstraction), which was that the abstraction applied corresponds to the current groundwater withdrawal conditions on Funen. A comparison of the results form the two different scenarios with respect to differences in potentiometric heads enables an independent identification of areas where water abstractions may have caused long-term groundwater depletion.

RESULTS

Identification of types of GWBs in terms of inter-linkages to adjacent ecosystems

Among the 123 GWBs there are 85 that either contribute to river runoff according to the assessment of MMRD data and/or identified as aquifers where the potentiometric heads are high enough to explain a potential linkage to surface waters (in total 65 GWBs). Among these 85 GWBs, two will be classified as surface near/local, eight will be classified as regional/deep, three as deep and the remaining 72 fulfil the criteria of regional aquifers. It is important to notice that the main challenge to identify different types based on the above described methods is related to the fact that MMRD measurements are not available for all parts of the county river net.

Identification of areas where long-term groundwater depletion may occur

For the scenario representing the current water abstraction from GWBs on Funen, the total rate of water abstraction is 34 million m^3 $year^{-1}$. Figure 2 shows both the location of large waterworks

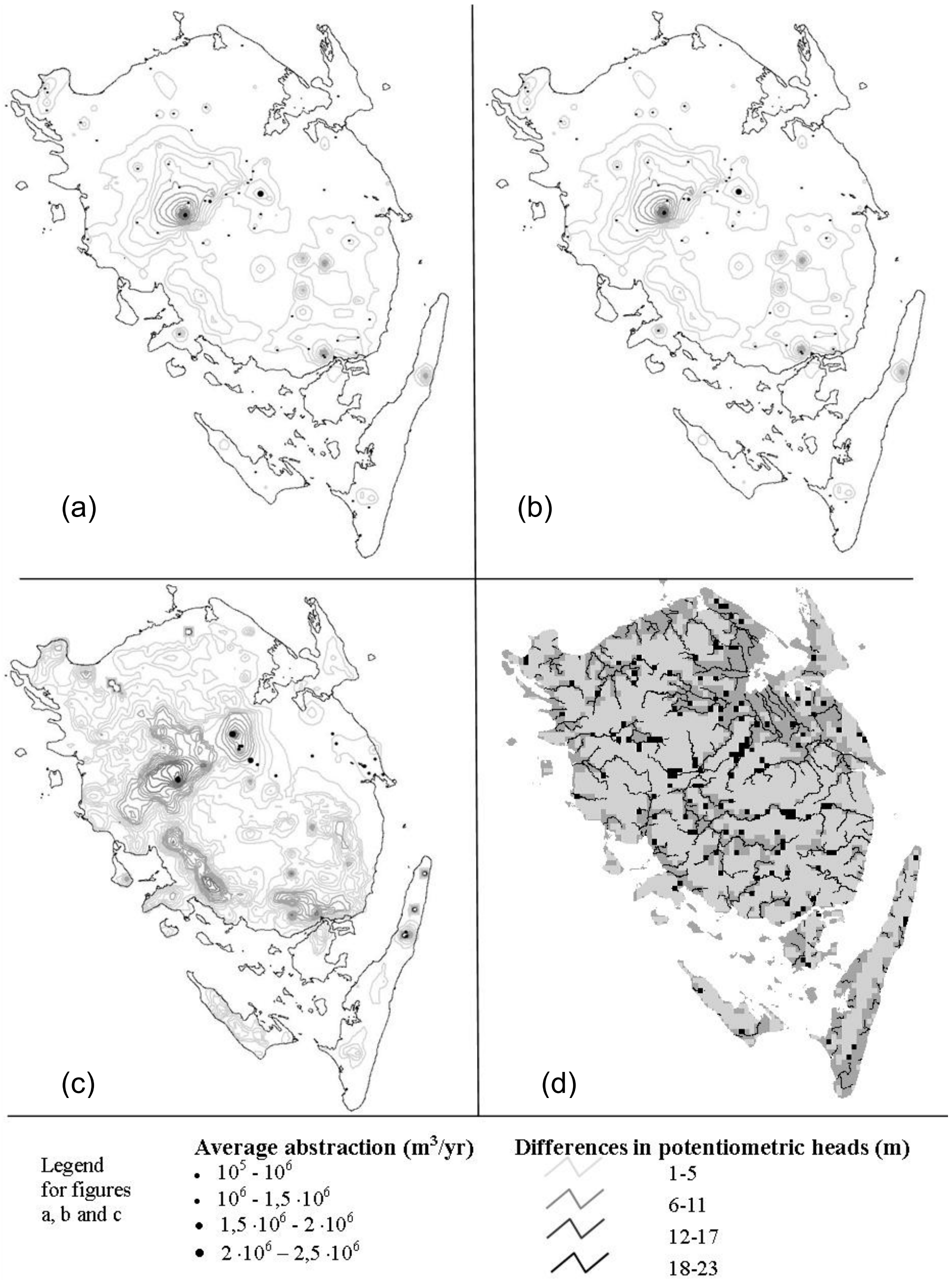

Fig. 2 Main water works and computed differences in potentiometric heads computed for the layers numbers 5 (a), 7 (b) and 9 (c) of the hydrological model, caused by water abstraction on Funen. Based on information on potentiometric heads in layer no. 5, the partial figure at the lower right (d) shows both cells (grey) where contact between GWBs and adjacent ecosystems (such as rivers (black lines) potentially exist and cells (black) where contact might be lost due to water abstraction.

withdrawing more than 100 000 m^3 $year^{-1}$, and the modelled effect of this abstraction on the distribution of potentiometric heads, affecting in turn biogeochemical processes (Mielby, 2006), river runoff (Müller-Wohlfeil *et al.*, 2003) and dependent superficial ecosystems (Procter *et al.*, 2006). Water abstraction is related to different geological units represented as four aquifer layers (denoted as layers 3, 5, 7 and 9) in the groundwater model. Differences in potentiometric heads for these four aquifers are calculated by subtracting average heads of the current conditions scenario from the pristine conditions scenario. According to the models results, abstraction leads to local head reductions of more than 12 m. The areas with highest groundwater table depletion are also the ones where MMRD changes become negative downstream.

DISCUSSION AND CONCLUSIONS

The fact that the identification of 50% (65 out of 123) of the GWBs of the Funen database being regional GWBs could be purely based on potentiometric head information indicates that this subsurface information is important with respect to locating areas which are currently affected by groundwater abstraction. A number of cells, which under pristine conditions indicated an inter-linkage between GWBs and adjacent dependent ecosystems, will not show up under current abstraction conditions, indicating that for 2% of the total area the linkage will be lost or cause inflow from rivers and lakes to the GWBs (Fig. 2). Figure 2 shows also that the largest impacts are related to abstraction from larger waterworks. An intercomparison of the results from the different layers indicates that effects can partly be seen at layers above or below the ones where abstraction occur, signifying spatial linkages between different adjacent GWBs.

Generally, the approaches applied have proven to be useful and repeatable for the regional-based analysis of the WFD, supporting the detection of areas where GWBs potentially contribute to river runoff and thus are in danger of impacts of water abstraction. Pin-pointing of areas exposed to potential abstraction impacts is an important issue as it can give valuable help to address and thus focus the monitoring network.

It is, however, important to consider a number of restrictions for the application of the current methods, which needs improvement. The spatial and temporal resolution of all available information is heterogeneous. The spatial resolution of the groundwater model operationally available for the approach to be applied regionally for all parts of Denmark is still 1×1 km^2, both with respect to the climatic input data and the representation of geological structures. The model has been established with a special focus on drinking water supply, mostly from deeper geological layers, which implies that the representation of shallow geological structural and times series necessary for model calibration and validation of processes near to the terrain surface is rather limited. Another problem users of the method have to cope with is the fact that MMRD values in many cases have been sampled during many different years and hence runoff conditions, hampering comparison along a water course. Accordingly, new repeated synchronous measurements are necessary to account for changed conditions with respect to land use, water management and climate.

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