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title: **BEST: a tool to determine groundwater pumping effects on eco-systems under the Water Framework Directive**

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A critical problem under the Water Framework Directive and associated rules is determining effects from groundwater recovery on terrestrial and aquatic ecosystems. In order for the Directive to be implemented comprehensively it is necessary to have methods that are easy and quick to apply while still being scientifically sound.

Analytical methods, such as are used in well test analysis, could be used to address these problems; however, there are many assumptions behind these methods and they are rarely satisfied. Furthermore, cumulative affects from multiple groundwater users should be addressed and the methods become clumsy when applied to large number of wells and the affected terrestrial and aquatic habitats.

The application of numerical groundwater models is another alternative, but these are specialist tools and require a special skill set to be effectively used. Furthermore, they are computationally intensive if to be used in an administrative environment.

We have developed a web-based application that permits accessing the computational accuracy and flexibility of the numerical groundwater models while keeping the user interface relatively simple (Figure 1).

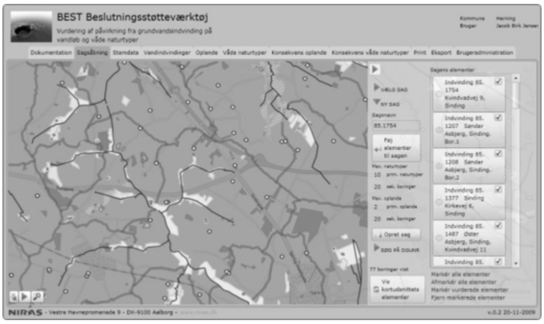

Figure 1. Map based dialog used to select the wells that are to be analyzed as well as showing the potential ecosystems that can be affected, multiple wells can be selected for analysis.

In order to do this we take advantage of the linear systems view of groundwater systems often used in optimization approaches to solving groundwater management issues. We calculate the response matrix for all wells in the county and use all other wells as well as terrestrial and aquatic biotopes as observation points. This response matrix provides the key to determining the effects from arbitrary pumping rates at a set of wells on the ecosystems in question (Figure 2). The response matrix needs to be tested for linearity.

A key in the methodology for developing the response matrix is to determine time-constants for seasonal abstractions. Irrigation abstractions from groundwater operate at high rates for only a few months each year. This means that the effect from these abstractions is a combination of a long-term average effect plus a seasonal contribution each year. A similar effect could be produced by some industrial groundwater users such as potato flour factories.

Key issues in implementation of the methodology will be presented. These include:

- The merging of existing groundwater models where there is model overlap,
- The development of pseudo-analytical numerical groundwater models for areas without existing numerical models, and

- The determination of cumulative effects from groundwater pumping on large fluvial systems.

The interface to applying the response matrix to determine effects is based on a web-service application (Figure 1), so all the data lies on a central server. This is important for data security, as well as facilitates the updating of information on ecosystems, hydrogeology and wells. While not implemented here, a web-service application opens the possibility for public distribution of say the resulting effects on ecosystems and other data/results that could be useful in public consultation on how to manage natural resources and ecosystems.

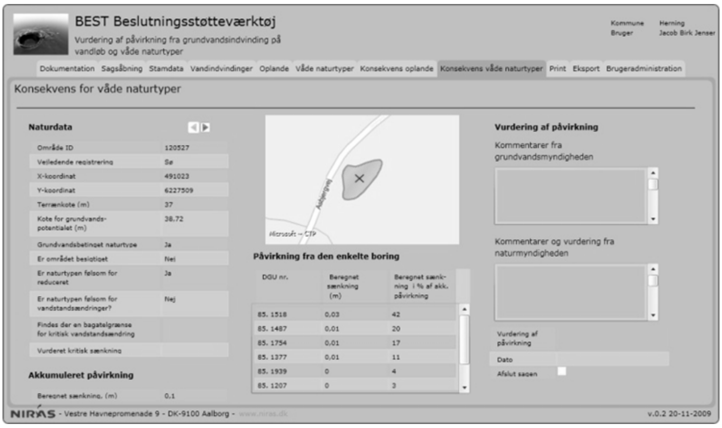

Figure 2. Dialog that presents the effects on each terrestrial ecosystem, note that each wells contribution to the effect is presented.

RESPONSE MATRIX

The foundation of the method is the response matrix. This is developed under the assumption that the groundwater system at hand behaves as a linear system. Given the boundary conditions applied in the numerical model for the simulations used to develop the response matrix this is a reasonable assumption. The boundary conditions used are drains and rivers; as well as constant head and no-flow boundaries. In development of the response matrix all pumping is injection to increase solution stability when the model needs to be run several thousand times for a water district.

The model is run for each well with a set injection rate and the effect on head is observed at all cells and flow effects are recorded at boundary condition cells. We disregard any effects less than respective user defined limits for head change and flow change.

The response matrix is stored on a database server so that every 100×100 m model cell that is for any injection is geocoded, and linked to the well(s) that affect water levels. Boundary conditions that are affected are managed in a slightly different manner, as it is necessary in the context of the WFD to see cumulative effects within a basin. So, in addition to geocoding the location along a river or in a wetland that is affected; it is also necessary to have these locations geographically linked to the catchment they lie in. Additionally it is necessary to have system for the interconnection of catchments so that one can see which extractors affect flows at some arbitrary point along a river system.

ABSTRACTION EFFECTS ANALYSIS

The work flow for determining the effects from an abstraction starts on a screen such as seen in Figure 1. The user selects which well they wish to determine effects for; this initiates a series of geodatabase server queries that result in identifying all the habitats and water bodies that are affected by the abstraction. Furthermore, all other abstractions that affect these areas, habitats or bodies are identified. This is an advantage of geoindexing effect features.

In order to determine the seasonal affects from irrigation abstractions or other seasonal groundwater uses; the groundwater model used to determine the response matrix is run as a transient model, where effects are recorded at a series of times across a year. The final time step is run as a steady-state time step (stress period) in order to show the long term effects from the abstraction in question.

The user verifies that the abstraction rate at the well to be evaluated is correct, if not the rate is adjusted. The user now can see the effects on water levels and flows. The user is also presented with the target status and sensitivity for each water body, and practical information such as when or if the body has been surveyed and the results of such a survey. The user can also see how much of the effect on each water body is from the well being evaluated versus the total effect. The may choose to see each wells absolute or relative contribution to the effects.

The method is rapid enough that the user can, in cases where the affect is unacceptable, use the tool to determine an acceptable abstraction rate. In principle one could apply optimization methods to reallocate abstraction permits.

EVALUATION DISSIMINATION

The results from the evaluation for an abstraction are stored on the database server, so that other system users have the information available. The results of the evaluation are also stored in PDF files, one for effects on terrestrial habitats and one for effects on surface water bodies. The report on terrestrial habitats also includes drawdown effects. Given the rules applied for the administration of groundwater abstraction in Denmark, we have not developed a report on the effects on other groundwater users.

CONCLUSIONS

We have presented a novel method for determining effects from groundwater abstraction in context of the WFD and Habitat Directive. This method is implemented as a web-based application that permits accessing the computational accuracy and flexibility of the numerical groundwater models while keeping the user interface relatively simple.

A key to the successful implementation of the method is the application of geoindexing and georeferencing at the database level so that the interrelated causes and effects from abstractions for habitats and water bodies can be quickly accessed.

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