Application of desktop GIS for decision support in groundwater management

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Abstract

In this paper, a split approach to decision support systems for groundwater management is proposed. In the initial phase, a model specialist performs data acquisition, model design and calibration, using an appropriate software package. As a result, a set of carefully selected basic management scenarios is generated. Simple superposition of these will allow to approximately solve a large number of variations of a class of management alternatives. For the phase of scenario analysis and decision support, the relevant data and the results of the base scenarios are transferred to a desktop GIS (ArcView). A convenient ArcView user interface was developed to formulate a scenario, do the required overlays of the base scenarios and visualise and characterise the impacts. For a case study problem of optimal well locations under a variety of constraints, this paper presents the development of base scenarios and the decision support tools developed for ArcView. The accuracy of the overlay results is determined by comparison with the results obtained by a full numerical simulation.

1 Introduction

Groundwater management of regional aquifers is commonly based on a comprehensive, hydrogeological and hydrological database and tools for modelling groundwater flow and transport. However, the decision problems are usually neither well structured nor unambiguous because of multiple objectives and criteria, uncertainty in the data, as well as
subjective and socio-political aspects. Scenario analysis proved to be a reasonable concept to find acceptable solutions. The reaction of the groundwater system to a range of different decision alternatives is investigated under different assumptions of aquifer properties, boundary and hydrological conditions.

Recently, a variety of software packages were developed that integrate databases, numerical groundwater models and evaluation tools to aid in scenario based decision support. In most cases, a relatively high level of convenience in the operation of the numerical groundwater models has been achieved through graphical user interfaces and interactive help systems. This allows to use these previously complicated tools without specific computer skills.

Most of these packages are graphical front-ends for well established modelling codes like MODFLOW, MODPATH, SUTRA, MT3D and similar codes. Among the most popular packages in this category are PMWIN (Processing Modflow for Windows (Chiang & Kinzelbach [1]), GMS (ECGL [2]), or Visual Modflow (Guiguer & Franz [3])). Generally, the terminology of the user interface is determined by the underlying model code and the user has to know about the specific implementation and coding of boundary conditions, array indexing schemes, parameters of the solvers, etc. Newer packages (e.g. GMS and ARGUS NE) attempt to offer a conceptual modelling approach, i.e. the groundwater system is developed rather independently of the later numerical discretisation. This is sometimes claimed to be a GIS oriented approach.

Common to all these packages is the fact, that the graphical analysis and visualisation tools are restricted to the information that is either input or output of the model. The possibility to compare results of different model runs is already a rare exception. In many groundwater management problems however, the prediction of the groundwater heads or flow pattern is not the primary goal. Rather, the impacts on agricultural production, rare plant societies in riverine forests, leaking waste dump sites or other consequences of groundwater management scenarios have to be assessed. This requires the combination of model results and information external to the groundwater model. Since much of this information has a spatial context, it was natural to couple groundwater models and GIS. Different levels of connecting GIS and groundwater models proved to be successful, from full integration with a common user interface of GIS and groundwater model (e.g. IHSI - IDRISI Hydrological Simulation Interface, Free University Brussels, (De Smedt [4]) via pre- and postprocessors (e.g. Fürst et al [5]) to loosely
coupled systems with a simple exchange of files between GIS and groundwater model (Fürst [6]).

All these approaches assume that modeller and decision maker can use the same system.

Despite of all advances in the user friendliness of numerical models and the attempts to avoid misuse of models, in many cases the modelling task in a groundwater management problem cannot be done by the end user but should rather be done by specialised, experienced modellers for several reasons:

1. Numerical modelling of groundwater flow and transport requires deeper insight into both, hydraulic and hydrological processes, as well as understanding of numerical problems and pitfalls. So far, this expert knowledge has not adequately been incorporated into user interfaces and pre-processors of model packages.

2. Set-up and calibration of numerical models are still complex and time consuming tasks. Decision makers may only be able to formulate and evaluate different management scenarios.

In this paper, a split approach to decision support systems for groundwater management is proposed. In the initial phase, an experienced groundwater modeller performs data acquisition, model design and calibration. The result of this step is a set of carefully selected basic management scenarios. For this purpose, any of the appropriate and available modelling tools can be used. If the base scenarios are well selected, simple superposition of these will allow to approximately solve a large number of variations of a class of management alternatives. For the phase of scenario analysis and decision support, the relevant data and the results of the base scenarios are transferred to a desktop GIS (ArcView®). Scenario analysis with consideration of a variety of criteria, that require processing of spatial information is done in an environment which is much easier accessible for decision makers with a background in different disciplines. With moderate effort, a convenient ArcView® user interface was developed to formulate a scenario, do the required overlay of the base scenarios and visualise and characterise the impacts. For a case study problem of selecting well locations under a variety of constraints, this paper presents the development of base scenarios and the decision support tools developed for ArcView®. The accuracy of the overlay results is determined by comparison with the results obtained by a full numerical simulation.
2 GIS Superposition

Assuming that groundwater flow is confined or that drawdowns are small compared to the thickness of the aquifer, drawdowns due to pumping are proportional to the well discharge. If the cones of drawdown of neighbouring wells overlap, drawdowns can be added to compute the total drawdown (Bear [7]).

An approximate solution by superposition is appropriate for management problems, where drawdown is the main „hydrological“ decision criterion, but other complex criteria, like accessibility of well locations, land ownership, proximity to pipelines, biotope zones etc. play a major role.

In the case study in which we apply the tools described in this paper, we had to assess the capacity of an aquifer near the Danube downstream of Vienna, Austria, for regional water supply. This area has heterogeneous hydrogeological properties, a very small-structured pattern of vegetation and is part of the Danube-March national park. The total capacity for withdrawal of groundwater from the area is good, but quite a large number of constraints have to be met for a well location to be „acceptable“:

1. The total drawdown of the groundwater table must be kept small (< 1 m) everywhere, in the forests even less than 0.5 m.
2. Generally, wells are not accepted in forests, but additional restrictions might be present also in the meadows, due to the special sensitivity of a national park area.
3. Access to wells for pipes and machinery should not require new paths through the forest.
4. Flow time from surface waters to a well (distance) should not be too short to avoid hygienic problems.
5. Individual wells should have a minimum discharge to be economically feasible and to keep the number of wells low and the length of pipelines small.

It is obvious, that only the drawdown criterion requires a hydraulic model, while the other criteria can be studied by GIS analysis and visualisation. The purpose of this paper is not to discuss the complete GIS based decision processes, but to demonstrate how also the computation of drawdown for a scenario of assumed well locations and discharge rates is implemented in a GIS framework that allows scenario based decision analysis in one convenient environment.
2.1 Preparatory steps in the groundwater model

We use a 2-dimensional finite difference numerical groundwater model with equally sized square grid cells in the „expert phase“. After a conventional set-up and calibration of the model, a few extra steps are required to prepare for scenario analysis by superposition in the desktop GIS ArcView®:

1. Create a polygon shape file representing the geometry of the model grid. An ID of each grid cell can be computed from its row and column index, which are also attributes in the attribute table.
2. Divide the model domain into zones of similar response to pumping; store zone identification code as attribute of the grid shape file. Zonation can be based on a classification of hydraulic conductivities or specific drawdowns derived from a „wandering well“ analysis. A feasible number of zones ranges between 5 and 10.
3. For each cell, also specify the maximum well discharge, for which an approximate solution by superposition is feasible.
4. For each zone, compute the drawdowns due to pumping in one typical well; save the drawdowns in the neighbourhood of the wells in a separate table for each zone. In these tables, location is identified by the row and column index of a grid cell relative to the well (Figure 1). The size of the neighbourhood depends on the radius of influence of a well with the anticipated maximum drawdown.

2.2 Superposition for simulation of a well scenario

The procedure for computing the steady state drawdowns due to particular locations and pumping rates of wells requires a simple superposition of individual well drawdowns. The user places the desired number of wells with simple mouse clicks on a suitable background map. The pumping rates for each well are prompted from the screen, with a zone specific check that the rate is within a range where linear superposition is considered to give accurate results.

The procedure for computation of the approximative drawdown of the groundwater table is illustrated in Figure 1 and follows 6 steps:

1. For each well location, look up the corresponding response zone in the grid shape file. Find the table of drawdowns for a characteristic well in this zone.
2. Modify the drawdown proportionally to the desired pumping rate.
3. Compute the absolute position of each cell in the neighbourhood of the well according to the location of the well and compute the
corresponding polygon ID in the polygon shape file representing the computational grid of the numerical groundwater model.

4. Based on this ID, join the table of an individual well’s response with the polygons shape’s attribute table, adding a new column of

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Figure 1: Schematic illustration of the computation of drawdowns by superposition
drawdowns due to a single well.

5. Repeat step 1 to 4 for each well in the scenario.

6. Compute the sum of drawdowns.

All GIS options for visualisation and further analysis are now available to support the decision maker (Figure 2).

2.3 User interface

A convenient user interface for the creation of a well scenario and computation of groundwater drawdowns was developed using the ArcView® programming language Avenue® and the Dialog Editor®
Hydraulic Engineering Software

extension. It adds a menu to an ArcView® „View“ document, having entries for creating a new scenario, add and remove a well, change the discharge rate, and start the computations. All results are placed in ArcView® document types (shape files and tables) and can therefore be analysed and visualised with the standard ArcView® functions. For convenience, the most frequently used displays are also wrapped into a „Postprocessing“ menu, e.g. a standardised thematic map of drawdowns (Figure 2).

Usage is extremely easy and requires very little action from the user: Running for example a scenario of 5 wells needs only 5 „mouse-clicks“ to enter the location of the wells, entering 5 numbers as the pumping rates and 2 more mouse-clicks to start the simulation and display a map of the computed drawdowns.

2.4 Comparison with results of numerical flow model

To assess the validity and accuracy of the solution achieved by superposition, the computed drawdowns were compared with the drawdowns computed by the 2D finite difference groundwater model which was used to prepare the base tables. In the vicinity of the wells, the mean drawdowns for both solutions are generally within a few centimeters. Larger differences (a few decimeters) arise, where a well is close to a boundary of two zones which have a different response to pumping. The reason is, that for the superposition, the complete zone of influence of a well is assumed to be within the same response zone, while actually a large part is in a zone of different characteristics. Major relative differences also occur at larger distances from the wells, where the drawdowns of multiple wells should add up. However, in the base tables of drawdown only the vicinity of the wells are represented and not the theoretically infinite radius of influence.

Obviously, the approximate solution should be sufficient for a coarse allocation of wells, but exact locations and discharge rates of individual wells will depend on detailed local hydrogeological exploration including pumping tests.

3 Conclusions

The proposed split concept of a decision support system for groundwater management, which uses an approximate solution for the computation of groundwater drawdowns in a desktop GIS offers several advantages:
• A thorough study of the groundwater flow is based on a well-proven numerical groundwater flow model and is performed by a "groundwater specialist". The accuracy and validity of the approximate solution can be assessed and the constraints easily implemented.

• The decision maker, who has to consider not only groundwater related criteria, but also other environmental and economic criteria, can do a "safe" scenario analysis in one convenient Desktop-GIS environment offering only the subset of groundwater hydraulics needed for the problem. He will not be overwhelmed by the full catalogue of options in a groundwater modelling package.

• Implementation of the procedures for superposition could utilise the standard ArcView® document types which can be manipulated quite conveniently in the Avenue® language.

References


