Using GIS, MODFLOW and MODPATH for groundwater management of an alluvial aquifer of the River Sieg, Germany

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Abstract During the past years Geographic Information Systems (GIS) have been increasingly applied for geohydrological research studies and water resources assessments. However, the coupling of GIS with geo­hydrological models is still a subject for future research. To evaluate the benefits of linking a GIS with the groundwater model MODFLOW, the alluvial sediments of the lower Sieg River catchments were selected for a case study. The aquifer is located east of Bonn. It is bounded by the Rheinische Schiefergebirge in the south and the rivers Sieg and Rhine in the north and west. The study area covers about 45 km² and groundwater extraction is supporting the water supply of about half a million people. Two-thirds of the groundwater recharge is attributed by stream leakage of the Sieg River and the rest is recharge from infiltrating precipitation. Using MODFLOW, the infiltration parameters of the River Sieg and the hydraulic conductivity were calibrated in a stationary approach. Subsequently, parameters were verified and optimized for a transient model, based on 120 time steps of 1 month. The particle pathlines were calculated using the groundwater particle tracking code MODPATH. MODFLOW simulated the groundwater dynamics in the aquifer with good fit to the observed data for steady-state and transient conditions and grid-based leakage terms could be defined. Future research will focus on the linkage of MODBRANCH and MODFLOW for a better simulation of the river dynamics and the integration of the GIS ARC/INFO.

INTRODUCTION

In Germany about 90% of the total groundwater production is provided by alluvial aquifers, which receive recharge by infiltration of rainwater and river bank storage. Considering the increasing demand of this water resource in the future as well as the qualitative affects caused by human activities, groundwater protection against pollution from various types of land uses became a paramount issue in water resources management. The use of Geographic Information Systems, combined with application of mathematical models has significantly expanded our ability to understand and manage the water resources (Friedman et al., 1984), both in terms of quantity and quality.

Geographic Information Systems such like the PC-based GIS IDRISI (Eastman, 1992) provide a flexible tool for water resources management (Flügel, 1995; Kovar &
Nachtebel, 1993), as data pre- and postprocessing can be automatized to a high degree. Additionally, the raster database of the GIS permits an efficient data transformation between the spatial distribution represented in the GIS and the areal discretization obtained by the groundwater model using finite elements or finite differences.

Commonly used finite difference models in groundwater hydrology are based on the mathematical techniques developed by Trescott et al. (1976) or those of Prickett & Lonnquist (1971). Both models have been widely used in the United States, are well documented and are available for IBM-compatible personal computers at nominal cost. Regional applications in Germany, however, are very limited and often not documented. MODFLOW (McDonald & Harbaugh, 1988) is a three-dimensional, modularly structured open system groundwater flow model and is a further development of the Trescott model (Trescott et al., 1976).

In this case study the raster GIS IDRISI, the finite element model MODFLOW and the particle tracking code MODPATH (Pollock, 1989) were applied to simulate management strategies for the alluvial aquifer of the lower River Sieg supplying water for half a million people in the area near Bonn, Germany.

OBJECTIVES

The purpose of the study was a very practical one. The aim was to establish a regional management system which consists of a GIS database and a mathematical model to understand the aquifer system and to develop guidelines for further water withdrawal. Applying a 10-year data set, the GIS IDRISI was linked to the groundwater flow model MODFLOW. This main goal is threefold, containing the following steps: (a) the groundwater flow model MODFLOW was calibrated using the particle tracking program MODPATH for steady-state and transient conditions, (b) the performance of the MODFLOW modules RIV and STR1 (Prudic, 1989) describing the interaction of the aquifer and the River Sieg to delineate areas of different seepage dynamics was analysed on a grid cell basis; and (c) the groundwater model was linked with the raster GIS IDRISI and a database for aquifer management.

SYSTEM DESCRIPTION

The alluvial aquifer of the River Sieg, a tributary of the River Rhine, is located on the northern bound of the Rheinische Schiefergebirge, Germany. It is part of the tectonic subsidence of the Niederrheinische Bucht which started to decline in the Eocene (early period of Tertiary). The Tertiary clay as impervious layer builds the lower non-flow boundary condition underlying the alluvial gravel sediments which were accumulated in the Pleistocene. The clay layer throughout the whole area was interpolated within the GIS, based on over 200 boreholes. The Pleistocene terrace system distinguishes three different terrace levels. They are composed of gravel formations originating from the River Sieg and the River Rhine. Its petrographic spectrum is a homogeneous composition of white quartzites, sandstones and grey-white clayey shales. The average depth of the Pleistocene deposits is increasing from the lower to the middle terrace from 13 to about 20 m. All of them consist of predominantly coarse gravel, which is well-rounded.
Inclusions of sandy layers are found in the two older terraces. Depending on the
heterogeneity of the gravel deposits, hydraulic conductivity varies from $2.0 \times 10^{-2}$ to
$2.0 \times 10^{-3}$ m s$^{-1}$. The hydraulic conductivity was determined using flownet analysis,
pumping tests and granumetric analysis on various points.

**CONCEPTUAL MODEL FOR MODFLOW**

The conceptual model for MODFLOW is depicted in Fig. 1. The conceptualization has
to be carried out before the numerical simulation. It determines the dimensions of the
numerical model and the design of the grid. As shown in Fig. 1, the conceptual model
integrates the data and includes (a) the hydrogeological framework, (b) the physical
framework, (c) a detailed description of the water budget, (d) the physical and hydraulic
boundary conditions, (e) estimates of groundwater sources and sinks, and (f) information
about regional flow paths (Anderson & Woessner, 1992).

By using GIS techniques, the process of conceptualization and the selection of data
can be aided easily to help the modeller to make the best choice. For the lower Sieg
basin, the following methodology was applied: (a) the geohydrological data of a 10-year
period (1984-1993) including observations of groundwater heads in 200 wells, discharge
measurements of the River Sieg and the River Rhine and climatological data, all stored
in a project database, (b) a digital elevation model (DEM) having a $50 \times 50$ m grid size

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**System Input**

<table>
<thead>
<tr>
<th>Hydrogeological framework (1)</th>
<th>Water withdraw (5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrometeorological data (2)</td>
<td>Vegetation (6)</td>
</tr>
<tr>
<td>Potentiometric surface (3)</td>
<td>Topography (7)</td>
</tr>
<tr>
<td>Surface hydrology (4)</td>
<td></td>
</tr>
</tbody>
</table>

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**Conceptual Model**

| (1,3) basin boundaries (A) | (3) starting heads (B) |
| (1) hydraulic parameters (C) | (2,4,6,7) evapotranspiration rates (D) |
| (2,4,6) recharge rates (E) | (4,5) discrete flux (F) |
| (4,7) channel routing (G)  | Modem Arrays          |

- **BAS (A,B)**
- **BCF2 (C)**
- **GHB (A)**
- **STR1 (C,G)**
- **EVT (D)**
- **RCH (E)**
- **WEL (F)**

The numbers and letters indicate the direction of flow.

**Fig. 1** Conceptual model for development of arrays for MODFLOW.
resolution was imported into the GIS, together with digitized geology, soil and land use maps, and (c) using overlay analysis maps of the hydraulic conductivity, the transmissivity and groundwater recharge areas were derived. As a result of the conceptualization, the MODFLOW model arrays were constructed within the GIS and PROCESSING MODFLOW (Chiang & Kinzelbach, 1993) and by using a data transfer module converted into MODFLOW for the numerical simulation. A data transfer *vice versa* was additionally implemented.

**MODEL RESULTS**

The finite element groundwater model MODFLOW was calibrated for the alluvial aquifer of the River Sieg by calculating hydraulic heads as well as drawdowns for steady-state and transient conditions. Additionally, the water budget of the aquifer and particle travelling times were calculated using MODPATH. The aquifer of the study area and its discretization is shown in Fig. 2. Its boundary conditions are given by the River Rhine in the west, and the River Sieg in the north (specified boundary flux), and by the barrier between the Tertiary sediments and the gravel deposits in the southeast (specified boundary groundwater head).

![Fig. 2 Study area of the lower River Sieg, Germany, showing the model grid, the three reference groundwater wells and the boundary conditions.](image-url)
Steady-state and transient simulation

Based on the adopted conceptualization, the steady-state calibration yielded the following results: (a) groundwater recharge consists of 30% recharge from precipitation and 70% of seepage from the River Sieg, (b) inflow along the southeastern boundary is negligible, and (c) flow paths computed by MODPATH indicate travelling periods between 5 month near the production wells and about 10 years at the southeastern boundary of the aquifer.

The transient simulation was based on the insight obtained by the steady-state model. Twenty-seven groundwater observation wells and three production wells were selected for the calibration exercise. From the evaluation of measured and simulated variation in hydraulic head (over 120 time steps of 1 month), areas of different infiltration were delineated. Simulated and measured hydraulic heads are shown in Fig. 3. Curve I at the production well S141 reflects the variation of hydraulic head in the River Sieg. The groundwater recharge is strongly influenced by the flow dynamics in the river. At the observation well S161 (curve II), this influence has decreased considerably, and curve III for observation well S204 shows the dynamics of the aquifer recharged only by infiltrating rainfall, indicated by small amplitudes of the head-time curve. All three curves, however, show a very good fit between simulated and measured hydraulic heads described by correlation coefficients of $r = 0.91$ for curve I, $r = 0.89$ for curve II and $r = 0.80$ for curve III. The dynamics of infiltration between the river bed and adjacent aquifer obtained from the steady-state simulation was verified by means of several transient runs.

Stream-aquifer interaction

To account for the interaction between the aquifer and the two rivers Rhine and Sieg, the MODFLOW modules RIV and STR1 were used to simulate seepage from the aquifer
into the rivers and *vice versa*. The utilized concepts simulating the stream-aquifer interaction are based on a linear function of the hydraulic head and the stream stage. The flow values are calculated using Darcy's law. The input parameters needed for this modelling task were derived from field data from gauging stations in the rivers Sieg and Rhine and the adjacent aquifer. They were optimized by various model runs.

For the steady-state simulation, the data were statistically analysed for every grid cell affected by the stream-aquifer interaction. According to the mean average and the variance eight different infiltration classes were distinguished. They are summed up in Table 1 showing the location of the grid cells, the infiltration area, the length of the infiltration channel, the leakage and the average infiltration. Considering the mean annual flow, the river seepage varies from about 90 l s\(^{-1}\) km\(^{-1}\) near the production wells to 5 l s\(^{-1}\) km\(^{-1}\) in the northern and western parts of the aquifer. Compared to other seepage evaluation in the area, the calculated values show a similar value range. Even at flood events the simulation results are of the same magnitude than former calculations. They range between 7 and 175 l s\(^{-1}\) km\(^{-1}\) for the above mentioned infiltration areas. For the Rhine River, values of over 500 l s\(^{-1}\) km\(^{-1}\) can be expected during high floods. The advantage of the applied method to former calculations is its distribution over the total infiltration area on a grid basis for all time steps.

**Table 1** Classes of infiltration areas giving the location of the grid cells, the infiltration area, the length of the channel, the leakage and the average infiltration. The location of the grid cells refers to Fig. 2. The numbers are counted from right to left, beginning at the diversion of Pleisbach and Sieg. The bold columns indicate the average values for the rivers Sieg and Rhine. For the Sieg River, the table shows two averages (for models STRI and RIV).

<table>
<thead>
<tr>
<th>Location of grid cells</th>
<th>Infiltration area (km(^2))</th>
<th>Length of infiltration channel (m)</th>
<th>Leakage (l s(^{-1}))</th>
<th>Infiltration (l s(^{-1}) km(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-4</td>
<td>0.06</td>
<td>1300</td>
<td>3.3 × 10(^{-6})</td>
<td>66</td>
</tr>
<tr>
<td>5-12</td>
<td>0.12</td>
<td>2200</td>
<td>1.1 × 10(^{-6})</td>
<td>22</td>
</tr>
<tr>
<td>13-17</td>
<td>0.04</td>
<td>900</td>
<td>1.1 × 10(^{-9})</td>
<td>9</td>
</tr>
<tr>
<td>Sieg (RIV)</td>
<td><strong>0.22</strong></td>
<td><strong>4400</strong></td>
<td><strong>3.3 × 10(^{-6})</strong></td>
<td><strong>33</strong></td>
</tr>
<tr>
<td>18-27</td>
<td>0.10</td>
<td>2000</td>
<td>1.1 × 10(^{-6})</td>
<td>4</td>
</tr>
<tr>
<td>28-37</td>
<td>0.04</td>
<td>800</td>
<td>2.1 × 10(^{-6})</td>
<td>89</td>
</tr>
<tr>
<td>38-80</td>
<td>0.10</td>
<td>2000</td>
<td>1.8 × 10(^{-6})</td>
<td>91</td>
</tr>
<tr>
<td>81-84</td>
<td>0.08</td>
<td>1600</td>
<td>0.7 × 10(^{-6})</td>
<td>3</td>
</tr>
<tr>
<td>Sieg (STRI)</td>
<td><strong>0.32</strong></td>
<td><strong>6400</strong></td>
<td><strong>3.3 × 10(^{-6})</strong></td>
<td><strong>40</strong></td>
</tr>
<tr>
<td>Rhine (RIV)</td>
<td><strong>0.28</strong></td>
<td><strong>1400</strong></td>
<td><strong>7 × 10(^{-6})</strong></td>
<td><strong>5</strong></td>
</tr>
</tbody>
</table>

**CONCLUSIONS AND FUTURE RESEARCH NEEDS**

The groundwater flow in the aquifer adjacent to the lower Sieg could be successfully simulated for steady-state and transient conditions using the finite difference model MODFLOW and MODPATH. The derivation of the conceptual model was obtained combining the raster-based GIS IDRISI with PROCESSING MODFLOW and
MODFLOW. The GIS based data model permits fast presentation and improved interpretation of the models input and output. In a second step, the MODFLOW modules RIV and STR1 were applied to delineate areas of different river bank seepage and the results were compared to existing data. The applied methodology enabled a fast evaluation of areally distributed grid-based infiltration rates. Furthermore, an analysis over all time steps is feasible. Based on the presented results, the following research needs can be defined: (a) to improve the simulation of the stream-aquifer interaction with regard to backwater conditions, to be done by linking the MODFLOW modules RIV and STR1 with MODBRANCH (Swain, 1994), and (b) to enable the use the GIS techniques for the conceptual model design, to be done by developing more GIS linkages to ARC/INFO.

Acknowledgement The authors are pleased to acknowledge the cooperation with Dr Keith Turner, Colorado School of Mines, Golden, USA, the US Geological Survey, Denver, USA (model code) and the Wahnachtalsperrenverband, Germany for the supply of the model data.

REFERENCES


