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For submission to
MODFLOW '98
Golden Colorado
October 4-8, 1998

Sponsored by
International Ground Water Modeling Center and
Office of Special Programs and Continuing Education
Colorado School of Mines

Work supported under a military interdepartmental purchase request from the U.S. Department of Defense, U.S. Army, through U.S. Department of Energy contract W-31-109-Eng-38.

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Using MODFLOW Drains to Simulate Groundwater Flow in a Karst Environment[1]

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ABSTRACT

Modeling groundwater flow in a karst environment is both numerically challenging and highly uncertain because of potentially complex flowpaths and a lack of site-specific information. This study presents the results of MODFLOW numerical modeling in which drain cells in a finite-difference model are used as analogs for preferential flowpaths or conduits in karst environments. In this study, conduits in mixed-flow systems are simulated by assigning connected pathways of drain cells from the locations of tracer releases, sinkholes, or other karst features to outlet springs along inferred flowpaths. These paths are determined by the locations of losing stream segments, ephemeral stream beds, geophysical surveys, fracture lineaments, or other surficial characteristics, combined with the results of dye traces. The elevations of the drains at the discharge ends of the inferred flowpaths are set to the elevations of discharge springs; the elevations at the beginning of the inferred flowpaths are estimated from field data and are adjusted when necessary during model calibration. To simulate flow in a free-flowing conduit, a high conductance is assigned to each drain to eliminate the need for drain-specific information that would be very difficult to obtain. Calculations were performed for a site near Hohenfels, Germany. The potentiometric surface produced by the simulations agreed well with field data. The head contours in the vicinity of the karst features behaved in a manner consistent with a flow system having both diffuse and conduit components, and the sum of the volumetric flow out of the drain cells agreed closely with spring discharges and stream flows. Because of the success of this approach, it is recommended for regional studies in which little site-specific information (e.g., location, number, size, and conductivity of fractures and conduits) is available, and general flow characteristics are desired.

INTRODUCTION

Conduit flow will prevail or at least be present in carbonate terrains in which any of the following features are present: sinkholes, dry valleys, sinking streams, or karren (Rovey, 1994). The aquifers with the highest proportion of flow along non-Darcian lines are probably those composed

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of limestone, where fissures and dissolution features may be enlarged to form conduits that can range in size from 0.01 to 10 m in diameter (Gale, 1983).

As discussed in the literature, modeling groundwater flow in a karst environment can be challenging and often produces results that are highly uncertain due to the complexity of flowpaths and insufficient site-specific information. In the past, many modeling approaches have been used to simulate flow in a karst environment: models using an equivalent porous medium in which flow is governed by Darcy's law (Anderson and Woessner, 1992); "black-box" approaches in which functions are developed to reproduce input and output system responses (recharge and flow at discharge springs) (e.g., Dreiss, 1989a,b); models in which the preferred flowpath is simulated with a very high hydraulic conductivity relative to the surrounding matrix material (up to eight orders of magnitude difference) (e.g., Teutsch, 1989; Mace, 1995; Eisenlohr et al., 1997); fracture network simulations in which individual fractures are mapped and then studied (Long et al., 1982; Long and Billaux, 1987); and open channel equivalents (Thrailkill et al., 1991).

A mixed-flow system in a karst environment is a combination of diffuse and conduit flow (Quinlan and Ewers, 1985; Field, 1993). Simulation of a karst system composed of dendritic paths (Milanovic, 1981; White, 1988; White and White, 1989) may require a great deal of site-specific information on the karst channels (e.g., elevation, slope, fill material, roughness, cross-sectional area, Reynolds number, Froude number, diameter, etc.). Because this information is difficult, if not impossible, to obtain, flow modeling in karst terrains is generally not performed, or simplifying assumptions are used.

For this study, preferred flowpaths in a karst environment are simulated by using the drain feature of the finite-difference code MODFLOW (McDonald and Harbaugh, 1988). The beginning of the preferred flowpath coincides with the location of a known surficial feature (e.g., sinkhole, lineament, fracture, dye release, etc.) and terminates at a surficial discharge point. Intermediate points are assigned on the basis of an inferred flowpath determined from losing stream segments, ephemeral stream beds, fracture lineaments, geophysical surveys, or other surficial characteristics, combined with the results of dye traces. The total discharge for the modeled conduit is the sum of the discharges of each drain along the flowpath.

This approach is similar to using a discrete singular fracture set model (Teutsch and Sauter, 1991) without incorporating detailed information on the fractures. Rather, the modeling addresses features on a scale of less than 100 m to several kilometers. This scale is most important when considering flow and transport (Thrailkill, 1986). The method avoids the numerical instability associated with modeling an extremely high permeability contrast between a preferential flowpath and the adjacent aquifer materials.

MODFLOW DRAINS

The drain feature in MODFLOW was initially developed to simulate agricultural tiles that remove water from an aquifer at a rate proportional to the difference in water level (head) between the aquifer and some fixed drain elevation, as long as the head in the aquifer is above that elevation (McDonald and Harbaugh, 1988). If the head in the aquifer falls below that of the drain, no additional water removal occurs. For the computations presented in this study, drain elevations at the discharge points of the preferred flowpaths were assumed to be equal to elevations of associated springs or levels in surficial receiving waters. At the upstream end of the flowpaths, the elevations were estimated from drilling logs, potentiometric maps of the shallow groundwater systems, and bedrock maps. Elevations of drains in model cells located along the flowpath were estimated by using linear interpolation between the two ends to produce smooth transitions between cells.

Adjusting drain elevations is a means of achieving model calibration. By changing the drain elevations and the length of inferred conduits, the match to target heads at site monitoring wells can be improved.

In addition to a drain elevation, the drain conductance must also be specified. This lumped parameter incorporates information on characteristics of the drain and its immediate surroundings, as well as the head loss between the drain and the aquifer (McDonald and Harbaugh, 1988). For simplicity, a high conductance value was selected to eliminate the need for drain-specific data that would be difficult to obtain and to simulate a free-flowing conduit. A value of 100 m/d per meter of conduit length was converted to drain conductance for each drain cell.

Prior applications of MODFLOW in karst settings have made use of the drain package by assigning a drain at each outlet spring (e.g., Yobbi, 1989). In this manner, the drain elevation could be determined accurately. However, the flow removed from the system by the drain is limited to seepage from the adjacent upgradient model cells. In the current study, connected pathways of drain cells simulate the conduit portion of mixed-flow karst aquifers and are conceptually more accurate and realistic. In addition to the case study presented below, the approach provided encouraging results for a National Priorities List site in Missouri, USA (Quinn and Tomasko, 1998).

CASE STUDY

The Lautertal dry valley is part of the Combat Maneuver Training Center (CMTC) near Hohenfels, Germany (Figure 1). In the vicinity of the valley, the shallow groundwater system is complex. The aquifer is composed of a network of joints, fractures, and cavities in the carbonate Malm Formation (Heigold et al., 1994; Meyer et al., 1990). Precipitation is subject to rapid runoff and likely infiltration through solution-widened fractures. Some of the infiltrating precipitation discharges rapidly to springs in the Lauterach River valley (Glennon et al., 1998). Recharge to the shallow flow system occurs by infiltration of precipitation and interaction with dolines, losing stream segments, and fractures. The overall direction of groundwater flow is toward the Vils River. No perennial surface water features exist; however, local ponding occurs in the vicinity of mature dolines.

Electromagnetic geophysical surveys were conducted using EM-31 and EM-34 equipment (Glennon et al., 1998). Lineament patterns interpreted from the resulting anomaly maps provided a basis for determining the locations of conduits or clay-containing solution-enlarged fractures in the shallow aquifer.

The Lautertal modeling domain includes the entire CMTC and was extended off base to the west and south to make use of regional flow boundary conditions (Glennon et al., 1998). Figure 1 shows the CMTC portion of 11 km by 18 km modeling area. More than 1,800 drain cells are concentrated in the portion of the modeling domain that has abundant geophysical lineament results and several tracer tests. Because the Lautertal area is the focus of this study, the grid in this area has the highest resolution, with cells of 100 by 100 m. Near the model boundaries, the grid-cell density

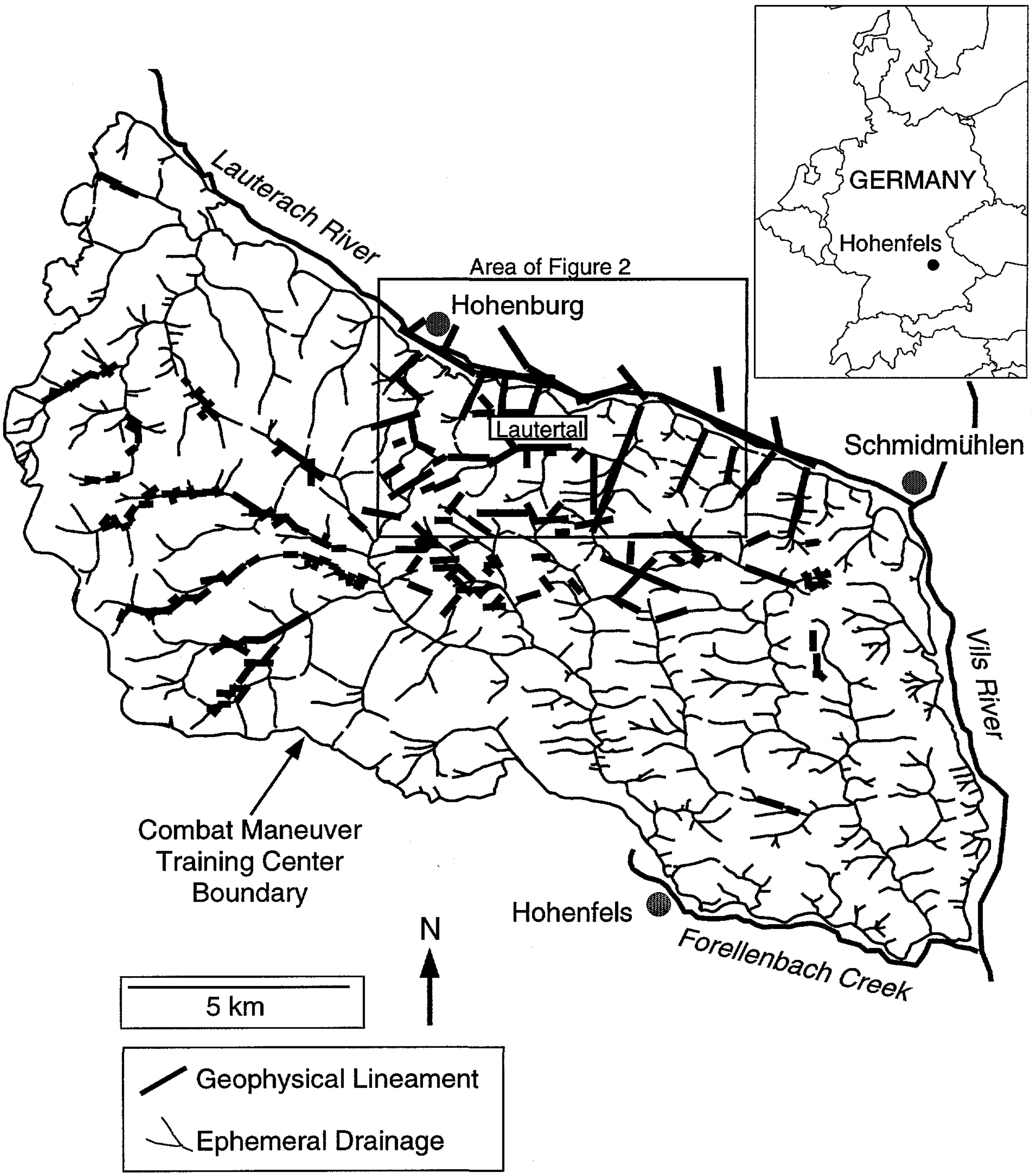

FIGURE 1 Location of the Lautertal Study Area, Geophysical Lineament Results, and On-Base Ephemeral Drainages

decreases, and the grid-cell size is 500 m by 500 m.

The Hohenfels site has a limited monitoring well network -- six wells located near the center of the modeling domain -- to be used for calibration purposes. A suitable calibration of the model was achieved by adjusting drain elevations to ensure active flow in all inferred conduits, then adjusting hydraulic conductivity to match the heads at the well locations (Glennon et al., 1998).

Figure 2 illustrates the implementation of the drains in conjunction with geophysical lineament data in the Lautertal vicinity, together with the flow vectors of the calibrated model. Localized changes in the direction of groundwater flow illustrate the interaction of groundwater with the adjacent surface water bodies and suggest that the boundary conditions for the model are defensible. That is, at the Forellenbach, Vils, and Lauterach Rivers, water-level contours bend upstream in an expected fashion. At the modeled conduits, the contours behave in the manner expected for a mixed-flow karst environment: a combination of diffuse and conduit flow. Groundwater converges on the preferential flowpath, and lines of equal potential point upstream.

The calibrated model's water budget indicates that, in the portion of the modeling area containing drains, most of the water that enters the system as recharge exits as conduit flow to springs rather than as diffuse discharge to the northern boundary, the Lauterach River. The computer code ZONEBUDGET (Harbaugh, 1990) permits a detailed analysis of the MODFLOW water budget. The predicted groundwater discharge along the southern bank of the Lauterach River between the westernmost and easternmost drains (approximately two-thirds of the model's width along the Lauterach) indicated a steady-state diffuse discharge of 46 L/s and a total conduit discharge of 810 L/s. The summed total discharge (856 L/s) is about one-third of the mean measured river flow in the Lauterach River at Schmidmühlen (Figure 1) of 2,800 L/s (Rothascher, 1987). Considering that approximately the same amount of flow enters the Lauterach from north of the modeled area, and a similar quantity enters the river from the remaining upstream third of both banks, the results indicate strong agreement between the steady-state simulation and the mean field data.

In addition, one-time spring gaging measurements are available for springs at Schmidmühlen (73 L/s) and Papiermühle/Hohenburg (205 L/s) (Herausgegeben vom Bayerischen Landesamt für Wasserwirtschaft München, 1990). Summing the flows from these major springs and others along the detailed portion of the Lauterach's southern bank could give a total flow similar to the 810 L/s calculated by the model. The calibration of the model could be improved if more spring gaging data were available.

SUMMARY

This paper presented a method of numerically modeling mixed flow in a karst environment by using connected pathways of MODFLOW drains to simulate conduits. The discharge ends of the preferred flowpaths were chosen to coincide with springs or other surface water features; initial points coincided with surficial features, such as dolines, geophysically determined lineaments, or the release locations of successful dye traces. Drain cells between the end points were assigned along the inferred conduit system. At the discharge end of the preferential flowpath, drain elevations were assigned on the basis of elevations of discharge springs and receiving waters. At the inlet end, the elevations were estimated from drilling records and from potentiometric surface and bedrock

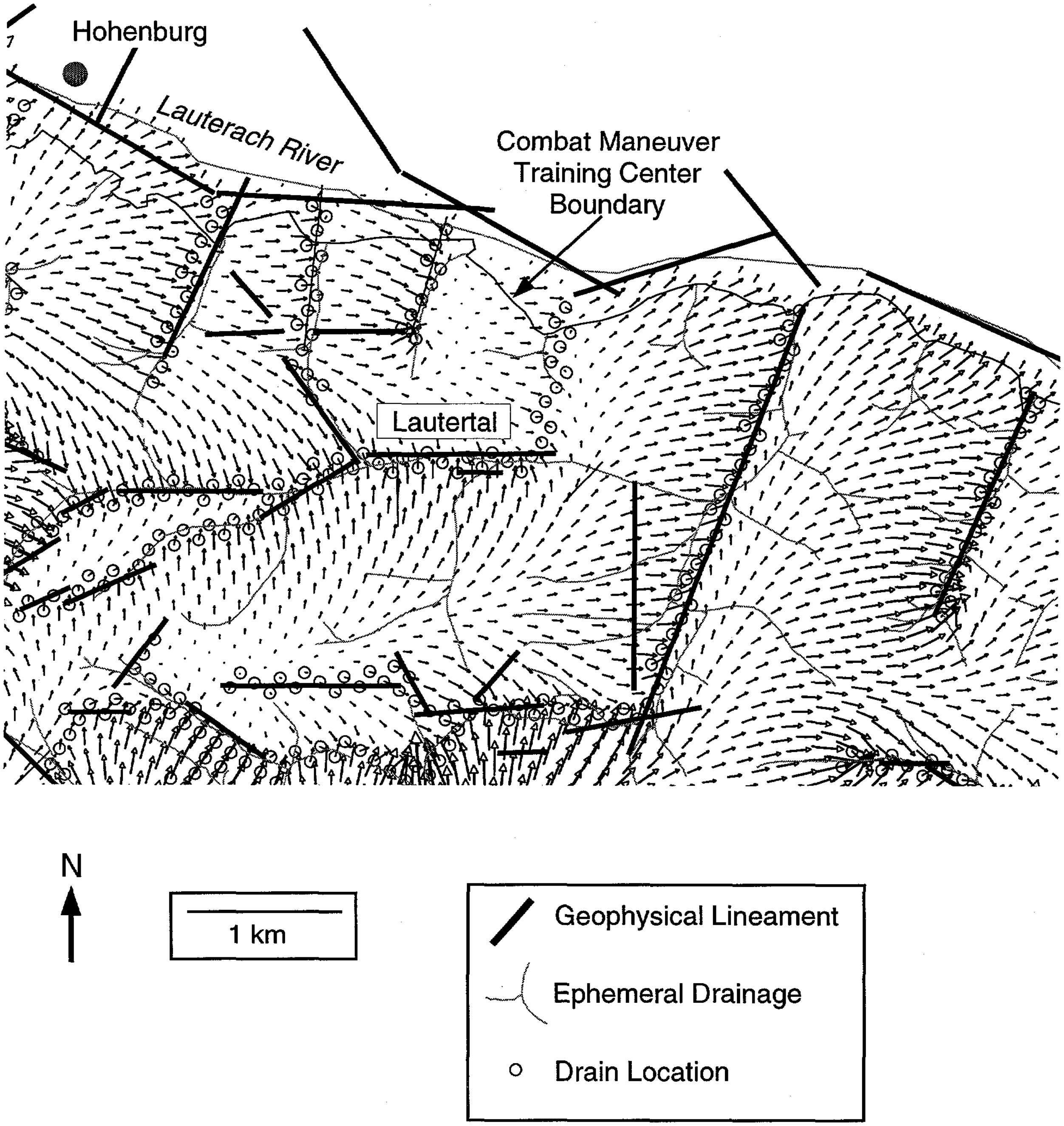

FIGURE 2 Drain Distributions in the Vicinity of the Lautertal and Groundwater Flow Vector Results of the Calibrated Model

elevation maps, and then were adjusted during calibration. Intermediate elevations were estimated by using linear interpolation. Drain conductance was set high to simulate free flow in a conduit and to eliminate the need for site-specific information. Total discharge from each conduit was the sum of the discharge from each drain along the conduit's flowpath.

Results obtained with the MODFLOW drain model compared well with field measurements (potentiometric surface and volumetric discharge) for a site near Hohenfels, Germany. Because of the success of this method, it is recommended for testing conceptual hydrogeologic models and for regional studies with limited site-specific information.

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