NRC EXPERIENCES IN HYDROCOIN:
AN INTERNATIONAL PROJECT FOR STUDYING
GROUND-WATER FLOW MODELING STRATEGIES

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ABSTRACT

The "Hydrologic Code Intercomparison Study" (HYDROCOIN) is an international study designed to investigate various ground-water modeling strategies used to analyze the performance of high-level waste disposal sites. The various ground-water models considered are to be used for safety assessments of low- and high-level radioactive waste facilities. The work completed to date has been simulations of test cases developed to verify and validate the numerical codes chosen by the individual project teams. Twenty-five computer codes were tested during the verification phase of the HYDROCOIN effort. To test the codes, seven cases, which include both saturated and unsaturated conditions in both fractured and porous media, were simulated. Simulation results from the 22 international project teams were then intercompared as well as compared to analytical solutions wherever possible. Current work deals with validation of ground-water flow models. After an exhaustive background study, it was determined that validation of complex ground-water flow models based upon a comprehensive data base is presently not possible. Therefore, the test cases accepted for the validation phase are for relatively simple ground-water flow systems where comparison of the simulation results are with limited field or laboratory data. Additionally, work dealing with uncertainty and sensitivity analyses has recently begun. This work explores appropriate ways of using hydrogeologic models in performance assessment by examining uncertainties in the conceptual models and the hydrogeologic parameters. Valuable lessons have been learned from the HYDROCOIN experiences in understanding limitations of the models, available data sets, and modeling strategies.

INTRODUCTION

HYDROCOIN Objectives and Framework

The "Hydrologic Code Intercomparison Study" (HYDROCOIN) is an international study designed to investigate the impact of various ground-water modeling strategies on performance assessments of radioactive waste disposal sites (1). After the success of their first international cooperative effort in the "International Nuclide Transport Code Intercomparison Study" (INTRACOIN) (2, 3), the Swedish Nuclear Power Inspectorate (SKI) organized the present effort on HYDROCOIN. The U.S. Nuclear Regulatory Commission (NRC) staff and their contractor, Sandia National Laboratories (SNL), participated in the INTRACOIN project and are currently involved in the HYDROCOIN study.

Based upon HYDROCOIN work to date, the NRC's Office of Nuclear Regulatory Research (RES) staff and SNL contractors have outlined certain important lessons learned from the corporate HYDROCOIN ground-water modeling experiences. These lessons are drawn from experiences with numerical simulations of both saturated and unsaturated flow problems dealing with various geologic media (e.g. fractured granite, clay, bedded salt) for both high and low-level waste disposal settings.

The HYDROCOIN study has three basic technical objectives:

(1) To verify the numerical accuracy of ground-water flow codes (verification).

(2) To study the capabilities of different ground-water flow models in describing laboratory and field experiments ("validation").

(3) To study the impact on the ground-water flow simulations by incorporating various physical phenomena (sensitivity and uncertainty analyses).

Level 1

The HYDROCOIN study is divided into three components termed Levels 1, 2, and 3 to accomplish each of the technical objectives. Level 1 investigated the accuracy of computer codes by simulating the following seven cases:

Case 1: Transient flow from a borehole in fractured permeable medium.

Case 2: Steady-state flow in a rock mass intersected by fracture zones.

Case 3: Saturated-unsaturated flow in a layered sequence.

Case 4: Transient thermal convection in a saturated permeable medium.

Case 5: Salt-water concentrations in a saturated porous medium.

Case 6: Three-dimensional steady-state flow in a regional aquifer.

Case 7: Saturated two-dimensional flow for near-surface disposal in an argillaceous medium.

The work completed to date has been simulations of these test cases developed to verify the numerical codes chosen by the 22 individual project teams (e.g., NRC, ONWI, PNL, SNL, NNWSI, AECL, AERE, BGS, CEA and others). The Level 1 studies tested 25 computer codes (e.g., CFEST, FEMWATER, METIS, SAGUARO, SWIFT II, UNSAT2, USGS3D, and others) over a range of seven cases for various saturated and partially saturated conditions for both fractured and porous media. The simulation results were intercompared as well as compared to analytical solutions where possible.

Level 2

Level 2 began as an attempt to validate ground-water flow models by simulating laboratory and field experiments. After exhaustive literature searches and inquires of other investigators, the group was unable to find experiments that contained data sets adequate for model validation. However, the group believed that the exercise of simulating field and laboratory experiments would provide valuable information about the codes and the modeling strategies. Therefore, five test cases were selected for Level 2. These cases are:

Case 1: Thermal convection (free and forced) and conduction around a heater experiment in a quarry in Cornwall, England.

Case 2: Salt convection analogue based upon a laboratory experiment on thermal convection.

Case 3: Granite block at AECL's Chalk River site in Canada.

Case 4: Large-scale regional ground-water flow system in the Piceance Valley, Colorado.

Case 5: Infiltration experiment performed in the Central Valley, California.

Level 3

In Level 3, the uncertainty associated with model results, and the sensitivity of model results to changes in model parameters and model conceptualization are to be examined. This effort includes not only the use of ground-water flow models but also tools and techniques used to quantify uncertainties and to analyze the sensitivity of model results to parameter changes. Six test cases have been defined for use in Level 3. In addition, a seventh case for Level 3 has been defined to quantify the errors associated with particle tracking algorithms. Problems with these algorithms were discovered during the Level 1 exercise and this Level 3 problem was designed to address concerns raised at that time. Following is a list of the Level 3 problems:

Case 1: Near-surface waste disposal in unconsolidated sediments.

Case 2: Unsaturated flow in consolidated tuff.

Case 3: Regional ground-water flow for a bedded salt system.

Case 4: Coupled ground-water flow and brine transport.

Case 5: Crystalline fractured rock problem with two alternatives;

5.a. Chalk River site in Canada,
5.b. Fjaellveden KBS-3 site in Sweden.

Case 6: Three-dimensional ground-water flow in permeable media.

Case 7: Particle tracking in a uniform flow field that contains a discharging well.

Level 3 problems have been defined but only initial simulations have been made.

HYDROCOIN Status

Presently, work on Level 1, model verification, has been completed and will be published soon. Level 2 work on model validation is scheduled to be completed by May 1987. Level 3 work on model uncertainty and sensitivity analysis is anticipated to be completed no later than November 1987 (4).

In order to illustrate the type of work performed in the Level 1 work and to report some of the HYDROCOIN findings, we have chosen two problems to discuss. The first is Case 2 of Level 1, which is a steady-state simulation of a flow field which contains two intersecting fractures and the second is Case 7 of Level 3, the particle tracking problem.

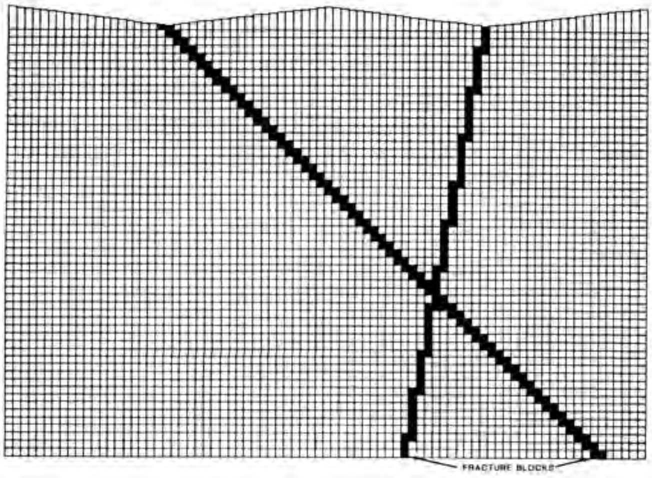
SELECTED SIMULATIONS

Steady-State Flow in a Rock Mass Intersected by Fracture Zones (Level 1,Case 2)

Case 2 of Level 1 was selected as an example simulation to illustrate some of the findings obtained in the HYDROCOIN study.

1. Problem Description

A steady-state flow system in a crystalline rock mass which contains two intersecting fractures was simulated in this case (see Fig. 1). The problem is two-dimensional (in the x-z plane) and the rock mass is assumed to be saturated. The purpose of this problem is to test different codes' abilities of handling large permeability contrasts. In addition, the effect of model discretization is to be investigated by requiring each participant to employ at least two different discretizations in solving the problem.



Assumptions

- Both matrix and fracture zones are isotropic and homogenous permeable media
- Flow can be described by Darcy's Law
- Matrix and fracture zones are saturated
- Steady-state flow
- Hydraulic conductivity in matrix 100 times lower than in the fracture zone
- No flow boundaries along A-B, B-C and C-D
- Ground-water level assumed to coincide with top boundary (A-G-F-E-D)
- Effective porosity for the fracture and the matrix is 0.03

Fig. 1. Conceptual model for simulating flow in crystalline rock with intersecting fracture zones (Level 1, Case 2)

2. Simulations Performed

Three sets of simulations were performed for three different codes; SWIFT II (See Refs. 5 and 6), FEMWATER (See Ref. 7), and USGS-3D (See Ref. 8) codes. Two of these (SWIFT II and USGS-3D) are finite-difference codes while the remainder (FEMWATER) is a finite-element code. Three discretizations were used in simulating the problem with the SWIFT II code while two different meshes were used with the FEMWATER code. In the USGS-3D simulation, only one grid was used. However, a different approach to accurately represent the fractures was taken, compared to that used in the SWIFT II simulation.

3. SWIFT II Simulations

As stated above, three different meshes were employed in the SWIFT II simulations using 4136, 2925, and 1148 nodes, respectively. Fractures were treated simply by assigning the hydraulic conductivity associated with the fracture to any block that was crossed by a fracture (see Fig. 2). Because of the finite-difference scheme, this resulted in fracture blocks not being directly coupled to each other for certain discretizations. Therefore, additional simulations were made where blocks adjacent to the fracture were given fracture properties in order to allow for a connection of blocks lying along the fracture.

An analytical solution for this case does not exist. However, two bases for comparison exist. One is to intercompare the SWIFT II results for the different grids and the other is to compare the SWIFT II results to those from other models. The hydraulic heads reported for all models were very similar. It should be noted that in the three SWIFT II simulations, the hydraulic heads near the fracture zones decreased with each finer discretization. With the finite-element model (FEMWATER), elements were constructed which corresponded exactly with the fractures; however, for SWIFT II, large rectangular blocks were used to represent different segments of the fracture. Thus, in the SWIFT II simulations, the effective width of the fracture was much greater than its real width. This in turn caused a greater reduction in hydraulic head along the fractures.

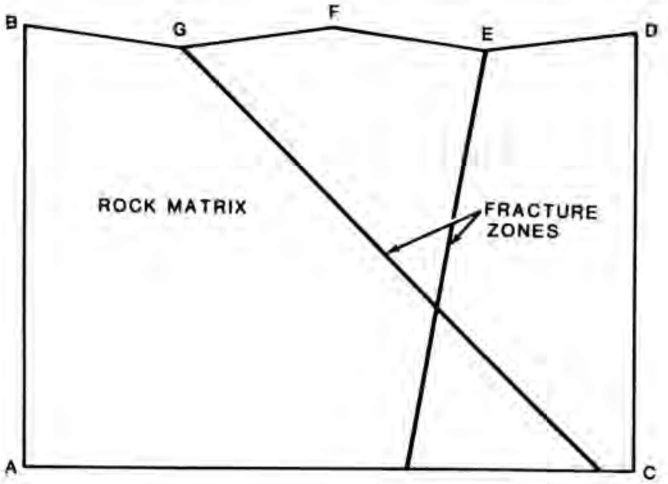


Fig. 2. Finite difference grid (4136 nodes) used in the SWIFT II simulation of the intersecting fracture problem (Level 1, Case 2)

Comparison of the simulation results were not only for hydraulic heads, but also for predicted flow paths. While hydraulic head profiles for the various code simulations compared well, differences were noted in the predicted pathlines when comparing the SWIFT II simulations with medium and coarse grids; the fine-grid SWIFT II simulation; and the results from fine-grid finite-element solutions. The reason for this is found in the nature of the model-predicted hydraulic head surface in the region where the two fractures intersect. This surface indicates a ground-water divide in this region. For the medium and coarse meshes, the resolution of the model results is such that the pathline fell above the divide, but the more highly resolved results of the fine mesh revealed that the divide lies more toward the top of the model. This, in turn, caused the particle to travel down fracture G to fracture E and then to the surface (see Fig. 3).

Pathlines resulting from the SWIFT II and USGS-3D simulations appeared jagged near and in the fracture block. This effect was caused by the way the finite-difference model connects the fracture blocks. Overall lengths of the pathlines and their associated travel times are listed in Table I. With the exception of path 2, which was discussed previously, the results generally agree.

4. USGS-3D Code Simulations

The construction of a model for Case 2 presented special problems to the finite-difference codes,

TABLE I

Travel times and distances for pathlines predicted for Case 2 of Level 1 using the SWIFT II code

	MESH	PATH 1 Distance (m)	PATH 1 Time (yrs)	PATH 2 Distance (m)	PATH 2 Time (yrs)	PATH 3 Distance (m)	PATH 3 Time (yrs)	PATH 4 Distance (m)	PATH 4 Time (yrs)
1	COARSE	572	1037	1099	5388	469	709	1197	9245
2	MEDIUM	604	959	1068	5602	587	706	1234	7518
3	FINE	618	1065	1757	12590	631	754	1394	13605

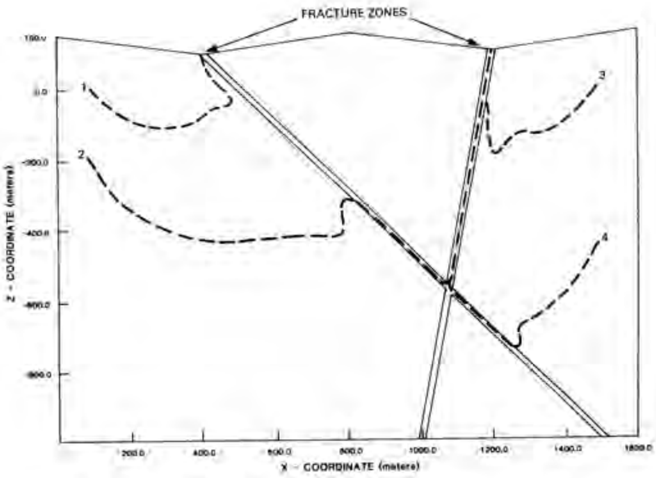


Fig. 3. Simulated particle trajectories for the fine grid used with the FEMWATER code (Level 1, Case 2). The pathlines originated at the numbered release points and exited the system either at fracture E or G

USGS-3D and SWIFT II codes. The problem required that two intersecting fractures, which are narrow relative to the scale of the problem and likely to largely control its hydrologic characteristics, receive the most detailed representation possible. The representation for both codes was obtained by maximizing the correspondence between the fractures and the location of the block centers. For the USGS-3D code, however, three additional steps were taken:

1. The grid was rotated relative to problem coordinates so that a column of block centers bisected the angle between the intersecting fractures.
2. One block was located at the intersection of the two fractures and the grid spacing was defined so that the fractures corresponded to diagonal lines in the grid.
3. The hydraulic parameters in the model were adjusted to provide a correction for flow along the diagonal lines representing the fractures, and to assure that the harmonic mean transmissivity calculated by the code produced the hydraulic parameters specified in the case description.

The correction made to accommodate the grid rotation is:

$$K'' = w_f K_f K_m \; (Dx^2 + Dy^2) \; / \; (4K_m Dy Dx - w_f K_f \; (Dx^2 + Dy^2))$$

where:

K'' = corrected fracture conductivity value (one value for each fracture)

K_m = matrix conductivity

K_f = fracture conductivity

w_f = fracture width

Dx = block dimension measured along a row

Dy = block dimension measured along a column.

The boundaries of the active grid were then located as near as possible to the actual boundaries of the problem. Blocks representing the head-potential boundary at the top of the profile were assigned potentials equal to the elevation of the model boundary at its closest approach to the block centers.

Results of the simulation were reported in terms of hydraulic head profiles and contours, and model-predicted pathlines. All of the results compared well with the other finite-element models and the finest grid used for SWIFT II.

5. FEMWATER Code Simulations

Two meshes were used to simulate this problem with the FEMWATER code. These meshes contain 112 and 378 elements respectively. The flexibility to use an irregular-shaped grid mesh in this finite-element code allowed for a more accurate representation of the geometry of the fractures than with the finite-difference codes (SWIFT II and USGS-3D). In addition, fewer total calculational points were needed to represent the whole system with this code (112 and 378 elements) than with SWIFT II (1148, 2925, and 4136 grid-blocks) or the USGS code (1885 grid-blocks). However, this does not necessarily mean that less time is required to set up and run the FEMWATER simulation.

The head distributions for the two meshes showed an expected increase in deviation with depth, which was also observed in the SWIFT II and USGS-3D simulation results. The resolution of head values in regions with a large head gradient was significantly affected by the discretization density. Head gradients in the low conductivity matrix were larger than gradients in the high conductivity fracture zones. Therefore, differences in head values for the two discretization densities decreased near the fracture zones. The head values for the two grids showed good agreement near the wider fracture zone. The reason for the largest deviation occurring at the lowest depth and the smallest deviation occurring at the highest depth, is that the head values on the surface were fixed by the imposed boundary condition. Head distributions for both discretizations were influenced by the fracture zones and therefore had a lower head value over the wider fracture zone.

As with the SWIFT II simulations, some problems associated with particle tracking occurred with the FEMWATER coarse mesh. Particle paths 1, 3, and 4 compared reasonably well with the results from other codes. However, for the coarse grid, the particle trajectory for path 2 never exited the grid and remained trapped within the middle area of the grid. This result is due to the numerical inaccuracies introduced by the use of too coarse of a discretization. A correct pathline was obtained for the finer discretization (see Fig. 3).

Efficiency of Particle Tracking Algorithms (Level 3, Case 7)

Pathline estimation from the results of a hydrologic simulation is often a first step in radionuclide transport analysis. In addition, estimates of ground-water travel time are used directly by the NRC in the evaluation of high-level waste disposal sites. As most models are not formulated to provide pathlines or stream function values directly, transport paths and their associated travel times must be obtained from calculations based on the simulated potential surface. The approximations made in these calculations compound the uncertainty associated with the potential solution. In addition, the accuracy of the flow paths may exhibit sensitivity to features of the model, such as grid density, independent of the potential solution itself. Therefore, this problem was designed to provide a means of comparing methods of trajectory (pathlines) calculation which is independent of the model employed to estimate the potential surface.

1. Problem Description

Pathline estimation from a hydraulic-head solution basically involves three steps: (1) estimation of the velocity field from the hydraulic-head solution; (2) the interpolation of the velocities to points along the travel paths and; (3) an algorithm to move the particles from one point to another. In order to remove the pathline estimate from the hydraulic head solution, an analytical solution for the potential and velocity fields was used as the starting point for the pathline calculation. The solution chosen is that for a single well discharging at a constant rate and located in a uniform flow field. The analytic solutions for the potential and the velocity components, when this well is located at the origin, are given in Ref. 9.

The important features of this flow field are the presence of a stagnation point, a ground-water divide and streamlines with significant curvature (see Fig. 4). Eight pathlines, selected to highlight the key features of the flow field, were used to compare the methods for trajectory calculation (see Fig. 5). For the comparison, project teams were requested to use three different gridding schemes in calculating the pathlines.

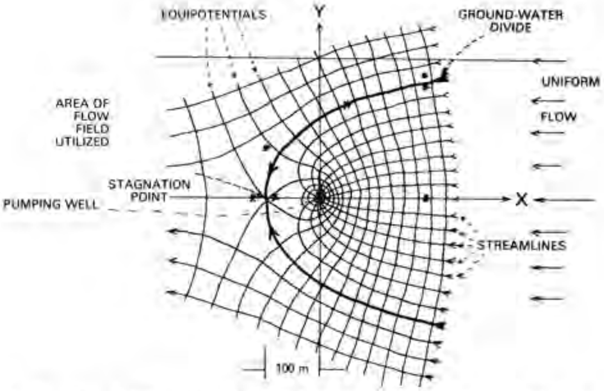


Fig. 4. Flow field resulting from a discharging well in a uniform flow field.
Note: The stars indicate the starting positions for the pathline calculations

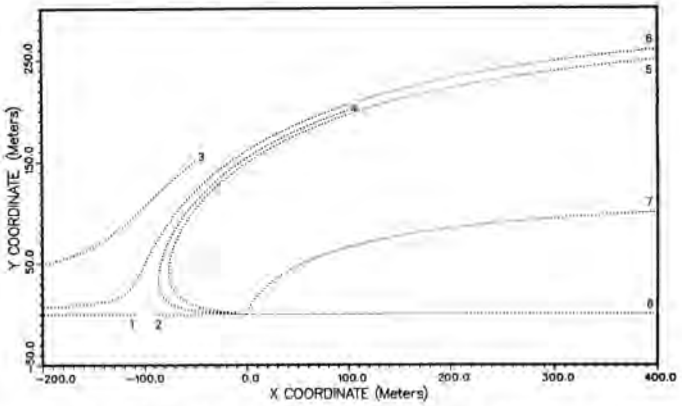


Fig. 5. Streamlines as calculated from the analytic expression for the stream function for the particle tracking problem (Level 3, Case 7). Numbers indicate the starting point locations for the eight streamline calculations

2. NRC Staff Simulations Performed

The NRC team attempted this problem with two different particle tracking algorithms. One was designed for use with the FEMWATER finite-element code, while the other was designed for use with the finite-difference codes, SWIFT II and USGS-3D.

The NRC staff constructed a trajectory calculation for use with the FEMWATER code that was based on a linear interpolation between nodal velocities. Particle trajectories were produced using a post processor with the FEMWATER output. The post processor estimates a particle trajectory through a finite-element mesh by the following process: (1) determine the specific element the particle is in; (2) linearly interpolate the velocity at the particle location from the four nodal values of the element; (3) determine the time increment needed to move the particle a distance equal to 2% of the smallest side of the element; (4) move the particle according to the previously calculated velocity and time step; and (5) print the location at every fifth time step.

Pathlines calculated with this method using both the analytic velocities and velocities calculated by the FEMWATER program are presented for a fine (20 meter nodal spacing) and coarse (120 meter nodal spacing) discretization in Figures 6 and 7, respectively. Pathlines associated with the fine discretization resolved the flow field quite well. Pathlines associated with the coarse gridding scheme exhibited significant deviations (e.g., crossing the groundwater divide, crossing a stagnation point). As expected, a linear trajectory calculation produced significant error when a coarse grid was used for a non-linear flow field.

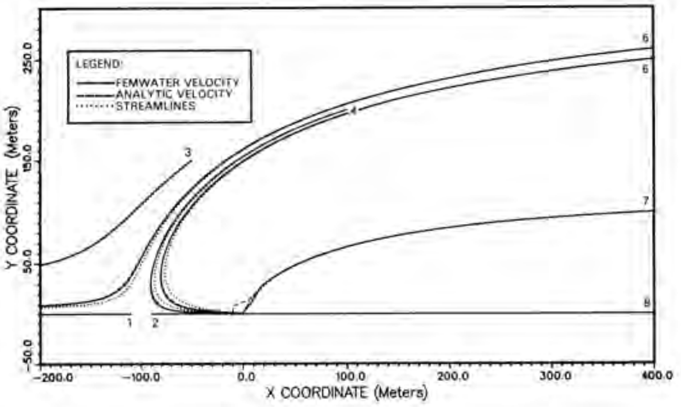


Fig. 6. Pathlines computed from both the analytic velocity field and the FEMWATER velocity field compared with the analytic streamlines for Case 7 of Level 3. The velocity fields utilized a grid spacing of 20 meters

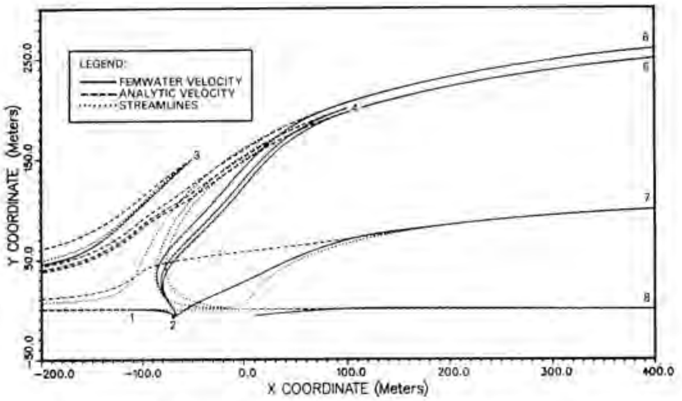


Fig. 7. Pathlines computed from both the analytic velocity field and the FEMWATER velocity field compared with the analytic streamlines for Case 7 of Level 3. The velocity fields utilized a grid spacing of 120 meters

3. SNL Simulations Performed

SNL's particle tracker, TRACKER, is designed to calculate trajectories from hydrologic model output based on finite difference solution procedures such as that used in the SWIFT II and the USGS-3D codes. This algorithm generates an analytical solution of the trajectory through each grid block assuming that, for each finite-difference block face, the component of velocity normal to the block face is constant. This approach prevents unstable oscillations of the calculated path between grid blocks, and eliminates the need for calculation of intermediate points inside grid blocks.

The results of SNL's tracking program for medium and fine (40m and 20m) grids compare well with the analytical solution. However, some deviation is displayed when the coarse grid (80m node spacing) was employed. Shown in Figure 8 are two of the predicted pathlines for the coarse grid. These trajectories show significant deviation from the analytical paths in regions of high curvature. The calculated path from release point 5 crosses the ground-water divide; however, both paths ultimately terminate on the correct side of the ground-water divide. Another method of quantifying the performance of each of the particle tracking post-processors is to calculate the deviation of the calculated pathlines from the analytical pathlines. This measure of error is defined at each point in the calculated trajectory to be the minimum distance between the point and the analytical trajectory from the release point. The error associated with the trajectories shown in Figure 8 is plotted in Figure 9. The flow paths show locally maximal deviation from the analytical solution at the grid block boundaries. The absolute maximum error occurs where the analytical flow paths have the greatest curvature.

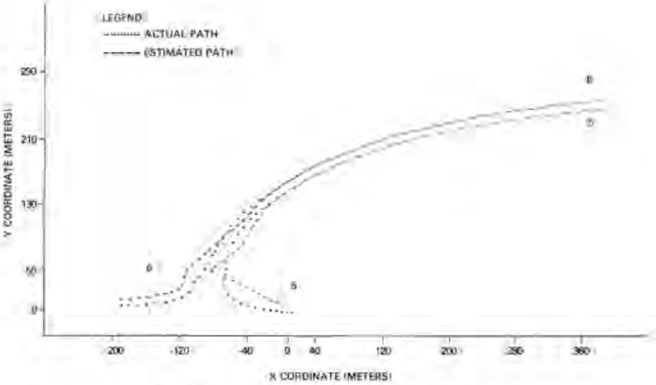


Fig. 8. Selected pathlines for Case 7 of Level 3 using the SNL tracking program. The tracking algorithm used the analytic expression for the potential with a grid spacing of 80 meters

Finally, it is worth mentioning that this problem involved an analytic solution for a homogeneous isotropic media in two dimensions. A more rigorous test of the trajectory calculation needs to be made where the effects of conductivity contrasts (i.e., fractured system) and/or three-dimensions are examined. The HYDROCOIN project secretariat is currently exploring ways to test these types of problems.

HYDROCOIN LESSONS LEARNED

Exercises similar to those described in this paper have been performed for all of the HYDROCOIN Level 1 cases (see Ref. 10) and selected Levels 2 and 3 cases.

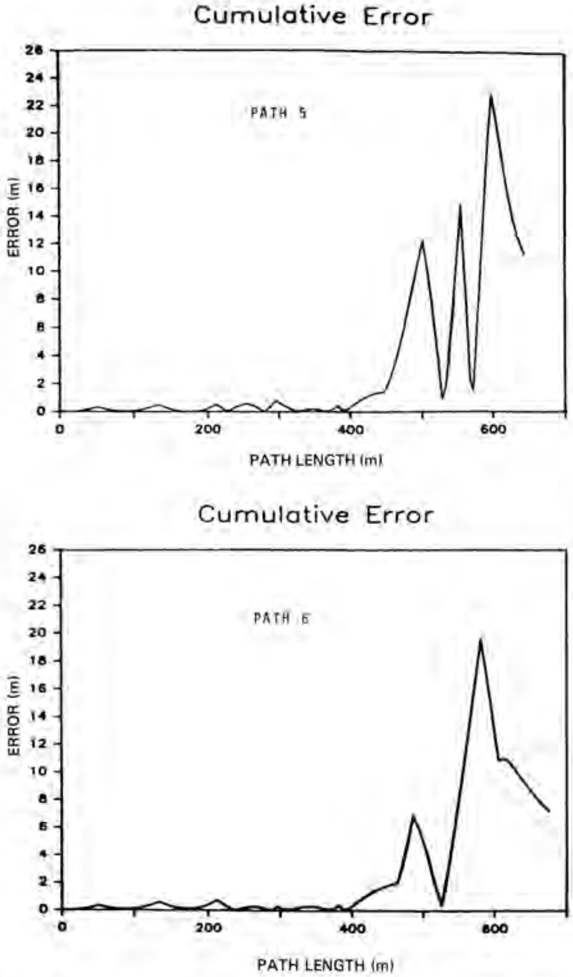


Fig. 9. Cumulative error associated with pathlines shown in Figure 8.

Based on these exercises and on discussions that occurred during the HYDROCOIN workshops, a summary of some of the important lessons learned from the HYDROCOIN ground-water modeling experiences are outlined below. Some of the findings of the study were previously known, while new findings have developed following the simulation work and subsequent technical exchanges. While some problems were identified, in general, the ground-water flow codes used in the HYDROCOIN study performed very well.

The following lessons learned are taken from Levels 1, 2 and 3 experiences.

Verification (Level 1) Lessons

1. Numerical simulation of ground-water flow problems which are linear in nature (e.g., saturated flow in permeable media) showed excellent comparisons for scalar quantities (e.g., hydraulic head, pressure, and temperature). However, for ground-water velocities the comparisons between HYDROCOIN project teams' simulations showed differences. For example, in Case 1 of Level 1, achieving accurate values for the flux to a well bore proved to be difficult for many codes.

2. In formulating ground-water model set-ups, grid orientations and discretization proved to be extremely important both for numerical convergence and for solution accuracy (e.g., pressure heads and velocities). The greatest problem in discretization arose when there were high permeability contrasts between adjoining hydrogeologic units. Grid orientation problems predominated when fracture orientations were not coincident with the permeability tensor directions inherent in the grid orientation. For finite element methods, the problems associated with fracture geometries were alleviated by both altering the grid size and by aligning the grids along the fracture direction. For both finite element and finite difference methods, the reorientation of the grid directions to coincide with the permeability tensors resolved the problem.

3. Surprisingly, finite-element and finite-difference method solutions for the same HYDROCOIN problems proved to be comparatively similar even for complex geometries (e.g., intersecting discrete fractures).

4. Non-linear problems involving hydrogeologic parameters which may be thought of as independent but are in fact functions of other variables (e.g., hydraulic conductivity as a function of density in a brine flow problem) posed great difficulty for all codes. The problems which caused the greatest difficulty involved unsaturated flow (Level 1, Case 3) and density driven flow (i.e., brine) (Level 1, Case 5). The transient part of the unsaturated flow (Case 3) problem proved too difficult for any code to simulate. Current numerical methods proved to be inadequate for many of the non-linear problems (e.g., density-driven flow associated with salt-brine diffusion) and resulted in both code modifications and/or selection of newly constructed codes (e.g., the USGS's SUTRA code (11)).

5. Although the codes provided adequate solutions for linear problems, the subsequent processing (post processors) of the output scalars into vector quantities, such as flux or particle trajectories, caused many difficulties. Perhaps most important is the recognition that adequate discretization for simulating the pressure or hydraulic head was not necessarily adequate for the particle trajectory calculations. Recognition of this type of problem is especially important in light of the fact that particle tracking is used in virtually all calculations designed to address the NRC ground-water travel time requirements, and further ground-water flow and transport codes designed to efficiently simulate radionuclide transport are network type codes, which require a particle tracking algorithm to define the paths that they will follow.

Validation (Level 2) Lessons

1. After extensive literature searches and inquiries of investigators outside the HYDROCOIN group, experiments that were adequate for model validation could not be found. The main problems with the available experiments were due to either incomplete parameter definition (both spatial and temporal) or to the lack of independent data sets useful for both model calibration and for evaluation of model predictions. In order to adequately validate these models, experiments formulated by both ground-water modelers and experimentalists need to be developed to provide the comprehensive data base required.

2. Simulations for the completed Level 2 problems required many iterations to arrive at solutions that adequately matched the experimental results. These interations involved numerous exchanges during the HYDROCOIN workshops. These discussions resulted in grid size, hydraulic values, time steps, and boundary conditions modification. While investigators benefited from the group interchanges, this approach results in a lack of independent results for the Level 2 problems.

3. Another problem with code validation, mentioned here because it is also a problem with real-site analysis, is the relationship between the confidence in model results and the type of performance measure used to imply that confidence. For example, in simulations of the Piceance Basin (Level 2, Case 4), the confidence that one had in the ability of the model to match the measured heads was dependent on whether an arithmetic mean, a root-mean-square error, or a kriged-weighted error was used to compare simulated with measured heads.

Uncertainty and Sensitivity Analyses (Level 3) Discussion

Level 3 work has recently begun, therefore, only initial simulations have been made and the definition of several cases are still being formulated. However, results of initial simulations and the discussions of the problem definitions have pointed out a few concerns about uncertainty and sensitivity analyses of ground-water flow models.

1. Performance measures need to be chosen prior to model simulation runs which address ground-water aspects that contribute most to transport (e.g., fluxes and stream lines).

2. Uncertainties in evaluating various conceptual models for a site should include varying hydrogeologic properties due to heterogeneities and varying boundary conditions. The uncertainties associated with the assignment of boundary conditions is perhaps more important than those associated with hydraulic parameters. Currently, no methods exist for quantifying the uncertainty associated with the formulation of conceptual ground-water flow models.

3. Particle tracking algorithms need to be developed for both two-dimensional flow in fracture media, and three-dimensional flow in porous media, in addition to the presently defined Level 3 case dealing with two-dimensional flow in porous media.

CONCLUSIONS

The extensive application of different hydrogeologic models to simulate carefully standardized ground-water flow problems has already made a significant contribution to understanding the limitations of (1) individual models, (2) modeling and calculational techniques and strategies, (3) available data sets for testing these models, and (4) methods for calculating and interpreting for numerical performance measures. The HYDROCOIN effort has also been extremely valuable as a forum for the exchange of information and experience on the application of these models.

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