HEATH HYDROLOGY GROUND WATER MODELING REPORT

DYNFLOW VERSION 5.18: TESTING AND EVALUATION OF CODE PERFORMANCE

by

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1. INTRODUCTION

While at the International Ground Water Modeling Center (IGWMC), Paul van der Heijde (currently an independent consultant working under the name Heath Hydrology out of Boulder, Colorado) has developed a four phase, three-level code testing approach, aimed at characterizing functionality and performance of ground water modeling codes (van der Heijde and Kanzer, 1996). This systematic approach to code testing combines elements of error-detection, evaluation of the operational characteristics of the code, and assessment of its suitability to solve certain types of management problems, with dedicated test problems, relevant test data sets, and informative performance measures. The results of code testing are expressed in terms of correctness (*e.g.*, in comparison with a benchmark), reliability (*e.g.*, convergence and stability of solution algorithms, and absence of terminal failures), efficiency of coded algorithms (in terms of numerical accuracy versus code execution time, and memory and mass storage requirements), and resources required for model setup and analysis (*e.g.*, input preparation time and effort needed to make output ready for graphic analysis) (van der Heijde and Kanzer, 1996). A revised version of this protocol has been adapted in 1996 by the American Society of Testing and Materials (ASTM) as D-6025: *Standard Guide for Developing and Evaluating Ground-Water Modeling Codes.*

According to the protocol described in ASTM D-6025, code testing should sequentially follow the following series of steps:

1. analysis of the code's functionality in terms of simulation functions, operational features, mathematical framework, and software implementation;

2. identification of potential code performance issues based on analysis of simulated processes, mathematical solution methods, computer limitations, and execution environment;

3. development of a code testing strategy and test problems that address relevant code performance issues as they are viewed by all stakeholders (*e.g.*, researchers, code developers, code users, fund managers, regulatory decision makers, project decision makers, etc.);

4. execution of tests and analysis of results using appropriate, comprehensive, informative and accurate graphic and statistical techniques;

5. collection of code information issues and code test problem objectives in overview tables and matrix displays reflecting completeness of testing, as well as correctness, accuracy, efficiency and field applicability of the tested code;

6. identification of performance strengths and weaknesses of the code and the testing procedure;

7. documentation of test objectives, model setup for both the tested code, and the benchmark (structure, discretization, parameters), and results for each test (for both the tested code and the benchmark) in report form and as electronic files including input data, computational

results, statistical analysis of computed results, and graphical representation of key results; and

8. preparation of an executive summary of functionality, test strategy and results.

The protocol makes a distinction between functionality analysis, and performance evaluation. *Functionality analysis* involves the identification and description of the functions of a simulation code in terms of model framework geometry, simulated processes, boundary conditions, and analytical capabilities, and the subsequent evaluation of each code function or group of functions for conceptual correctness and computational accuracy (including convergence for a practical range of parameter values) and consistency (including numerical stability). The information generated by functionality analysis is organized into a summary structure, or matrix, that brings together the description of code functionality, code-evaluation status, and appropriate test problems. The functionality matrix is formulated combining a complete description of the code functions and features with the objectives of targeted test problems. The functionality matrix illustrates the extent of the performed functionality analysis.

Performance evaluation is aimed at characterizing the operational characteristics of the code in terms of: 1) correctness, 2) overall accuracy; 3) reliability; 4) sensitivity for grid orientation and resolution, and for time discretization; 5) efficiency of coded algorithms (including bandwidth, rate of convergence, memory usage, and disk I/O); and 6) level of effort and resources required for model setup and simulation analysis. Results of the performance evaluation are expressed both quantitatively and qualitatively in checklists and in tabular form. Reporting on performance evaluation should provide potential users information on the performance as a function of problem complexity and setup, selection of simulation control parameters, and spatial and temporal discretization.

The functionality matrix and performance tables, together with the supporting test results and comments, should provide the information needed to select a code for a site-specific application and to evaluate the appropriateness of a code used at a particular site.

The code testing strategy represents a systematic, efficient approach to the comprehensive testing of the code. The code testing strategy includes:

1. formulation of test objectives (as related to code functionality), and of test priorities;

2. selection and/or design of test problems and determination of type and extent of testing for selected code functions or application-dependent combinations of code functions;

3. determination of level of effort to be spent on sensitivity analysis for each test problem;

4. selection of the qualitative and quantitative measures to be used in the evaluation of the code's performance; and

5. determination of the level of detail to be included in the test report and the format of reporting.

The protocol distinguishes four sequentially performed test phases:

1. conceptual testing -- highly simplified problems focused on testing individual functions, features, algorithms or code segments without necessarily comparing its results with a benchmark;

2. benchmarking or verification -- comparing results obtained with a computer code against independently derived solutions such as analytical solutions;

3. code intercomparison -- comparing compatible codes using hypothetical problems or synthetic data sets for which no independent solution is available; and

4. field or laboratory demonstration -- testing against well-documented field or laboratory experiments.

An important aspect of code testing is the definition of informative and efficient measures for use as evaluation or performance criteria. Such measures should characterize quantitatively the differences between the results derived with the simulation code and the benchmark, or between the results obtained with two comparable simulation codes. Evaluation of code testing results should be based on: 1) visual inspection of the graphical representation of variables computed with the numerical model and its benchmark; and 2) quantitative measures of the goodness-of-fit. Graphical measures are especially significant for test results that do not lend themselves to statistical analysis. For example, graphical representation of solution convergence characteristics may indicate numerical oscillations and instabilities in the iteration process. Statistical analysis typically consists of standard linear regression statistics and estimation of error statistics performed on paired data.

This report concerns the testing of the ground-water flow modeling code DYNFLOW (version: 5.18; release date: September 1994), developed by Camp Dresser & McKee, Cambridge, Massachusetts. The related documentation has as publication date April 1994. This report addresses two phases of testing: 1) evaluation of the testing performed by code authors in the past as described in the code's documentation, and 2) additional testing of the code by the author of this test report in cooperation with code's authors. As part of the evaluation of the performed testing, the code has been rerun using the data files prepared by the authors. This report provides an overview of the DYNFLOW functionality, summarizes the completeness of the earlier performed tests, identifies additional testing requirements, and analyzes the results of the performed tests. It includes discussion of the following activities:

1. identifying and examining code functionality;

2. determining type and objectives of tests performed and documented by the code developers;

3. compiling protocol summary structures (*i.e.*, checklists, matrices) using the performed tests;
4. evaluating test results as documented by code developers and reconstructed for this report;
5. identifying possible gaps in the test strategy used by the code developers and designing additional tests to address them; and
6. executing and evaluating the additional tests.

The code-evaluation tests for DYNFLOW were performed on a 200 MHZ Intel Pentium Pro based personal computer using Microsoft Windows NT 4.0. Evaluation plots were prepared with Golden Software's Grapher™ for Windows (version 1.0; Golden Software, 1992) and Microsoft Excel 95 and Excel 97.

2. TESTING DYNFLOW

2.1. CODE DESCRIPTION

The functionality of DYNFLOW has been determined using the generic functionality description form of van der Heijde and Kanzer, 1996, Appendix B; the results are presented in Appendix A of this report. A short description of DYNFLOW is given in the following paragraphs.

DYNFLOW is a general-purpose finite element code designed to simulate transient and steady-state three-dimensional saturated ground water flow under confined and unconfined conditions. Parts of the model domain may change in time between confined and unconfined conditions. The code supports both areal and cross-sectional two-dimensional simulations by reducing the third dimension accordingly. The code may be used for characterizing large, complex, multi-layered, fully-saturated, porous hydrogeologic systems. The code can be used in a quasi-three-dimensional mode.

The flow equation is posed in terms of piezometric head. It is assumed that fluid density does not change during the simulations. DYNFLOW includes calculation of a comprehensive, model-wide mass balance for flow, as well as node-specific fluxes (total net flux, fixed head flux, pumping flux, element recharge flux, and storage flux). Boundary conditions include specified head, specified flux, distributed recharge (at the water table), and evapotranspiration (based on evaporation potential and extinction depth). Head-dependent flux boundaries (*e.g.*, for leakage to or from streams, and flow to drains) are handled by including an extra layer of elements representing the stream/drain resistance, if present. The code includes "rising water" and "dry" boundary option to allow for water-table changes. Springs, seeps, and intermittent streams can be represented by the rising water condition. If a well is simulated in more than one layer, flow can be directly apportioned to the open layers, or represented using one-dimensional elements. Initial conditions can be specified through the input command file, or as a separate file containing heads calculated in previous runs (restart option).

Spatially variable flow parameters include hydraulic conductivity, specific storage or specific yield, recharge (applied only at water table), bulk specific gravity of overburden, and effective stress. The code handles general anisotropy in hydraulic conductivity (parallel to principal directions where principle directions do not have to coincide with Cartesian axes), stress-dependent hydraulic conductivity and specific storativity.

The DYNFLOW code employs linear finite elements, using any combination of four type of elements:

1. <u>three-dimensional elements</u> to represent flow in three directions (triangular discretization in the horizontal with orthogonal discretization in the vertical resulting in elements of varying thickness);
2. <u>two-dimensional elements</u> to represent vertical barriers such as faults and slurry walls;

3. one-dimensional elements to represent multi-aquifer wells, underdrains and fractured rock interconnections; and
4. pond elements to represent surface water bodies.

A typical DYNFLOW grid consists of a number of triangular elements in the horizontal direction, and one or more layers of variable thickness to represent the vertical dimension, resulting in column-shape three-dimensional elements bounded by parallel vertical lines. Elements can be grouped in up to 100 property zones. Element properties include hydraulic conductivity in the principal directions, the rotation angles for principal directions about the Z- and Y-axes, bulk specific gravity of overburden, and effective stress at which the properties are valid.

DYNFLOW includes 4 solvers: 1) Gauss, 2) SOR, 3) hybrid Gauss-SOR, and 4) ICCG. In the transient case, either a trapezoidal (Crank-Nicholson) or implicit time-stepping scheme may be used. The code is operated using user-specified commands (it uses an internal command language structure).

DYNFLOW is dimensionally consistent; any consistent set of units can be used.

The users manual contains sections on model theory and solvers, code operation and command processing, grid design and model formulation, representing stratigraphy, boundary condition processing, simulation of special features, run controls, analysis of output, use of units, calibration, code verification, and example problems.

2.2. TEST ISSUES

Based on the analysis of the functionality of the DYNFLOW code, a list of topics for further evaluation and testing has been compiled (see Table 1). Some of the listed topics reflect specific DYNFLOW functions (represented by program commands and input parameters); others are addressed by DYNFLOW through model formulation and construction (i.e., grid design and parameter allocation). For selected test topics, performance issues are formulated in terms of functional correctness (program logic, terminal failure, inconsistent results), accuracy, and stability; for other test issues objectives are stated in terms of applicability (availability, efficiency, completeness, and clarity). Tables 2A, 2B and 2C present the functionality issues, test objectives, DYNFLOW representation, and testing type for the code's general features, for hydrologic zoning, parameterization and flow characteristics, and boundary conditions, respectively.

The functionality items, listed in the first column of Tables 2A-2C, are represented by explicit code functions, or are addressed during model formulation and construction. The second column of Tables 2A-2C lists a qualifier for the test objective(s) for the selected function. The main (qualitative) objectives are: 1) correctness of computation(s), 2) accuracy of computation(s), 3) completeness of reported information, 4) stability (of numerical solution), and 5) applicability (how easy/difficult is it to use the code to represent particular function). The last column indicates the testing method.

Table 1. Test topics for the three-dimensional finite-element saturated flow code DYNFLOW.

General Features

- code operation (program controls, command structure, I/O instructions)
- output (completeness, clarity, format and layout, suitability for postprocessing)
- grid issues (grid geometry, element types, node/element numbering, automatic bandwidth reduction)
- element superposition (e.g., for multi-layer wells)
- stress superposition (multiple stresses at same location)
- solver(s) operation, accuracy, stability
- time stepping (step size, multiplier, stress period)
- mass balances (regular versus irregular grid; global, zonal, layer-wide, nodal)
- error trapping and clarity of error messages
- file processing (input files, output files, grid files)

Hydrogeologic Zoning, Parameterization, and Flow Characteristics

- steady-state flow
- transient flow
- horizontal flow
- vertical flow
- radial-symmetrical flow
- parameter zones (heterogeneity)
- aquifer pinchout, aquitard pinchout, dipping beds, outcrops, subcrops, and unconformities
- variable thickness layers
- storativity conversion in space and time (confined-unconfined)
- anisotropy (horizontal, vertical)
- changing principal directions
- unconfined conditions (rising/falling water table)
- sharp contrast in hydraulic conductivity (magnitude, principal directions, anisotropy)
- internal no-flow areas
- fracture zones (high conductivity; superposition)
- slurry walls (low conductivity; superposition)
- stress-dependent properties

Boundary Conditions for Flow

- default no-flow assumption (lateral, lower/upper boundaries)
- prescribed head (varying flux)
- prescribed flux (varying head)
- areal recharge in top active cells (water-table)
- induced infiltration from streams/sourcebed aquifer (leaky boundary) with potential for dewatering below the base of the semi-pervious boundary (constant flux/depth dependent flux)
- induced exfiltration towards stream
- drain boundary (no b.c. if g.w. head is below drain level)
- reservoir boundary (extent varies in time)
- model dries up (head below bottom of model domain)
- irregular geometry and internal no-flow regions
- time-varying discharging/ recharging wells
- multi-aquifer/multi-model-layer wells
- (depth-limited) evapotranspiration
- pond element
- springs/seeps
- seepage face

Table 2-A. Functionality Issues for General Features.

Functionality Issue	*Test Objective(s)*	*DYNFLOW Implementation/ representation*	*DYNFLOW Testing Method*
Program controls/command structure	correctness	code function	runtime testing
I/O instructions	correctness	code function	runtime testing
Form of output	completeness clarity format	code function	manual evaluation
Grid/mesh issues: element/node numbering (bandwidth reduction)	correctness	code function	runtime testing
Grid/mesh issues: element superposition (of 1D and 2D elements on 3D mesh)	correctness	code function	runtime testing
Stress superposition at individual nodes and time steps (pumping, recharge, evapotranspiration)	correctness	code function	verification
Solver performance (including sensitivity to iteration criterions, acceleration parameters, etc.)	correctness, accuracy, stability	code function	runtime testing, verification
Time stepping (specification of time step, multiplication factor, stress period)	correctness	code function	runtime testing
Mass balance (global, zonal, layer-wide, nodal)	applicability, completeness	code function	evaluation
Error trapping	correctness completeness	code function	manual evaluation, crash testing
File processing	correctness	code function	runtime testing

Table 2-B. Functionality Issues for Hydrogeologic Zoning, Parameterization, and Flow Characteristics.

Functionality Issue	*Test Objective(s)*	*DYNFLOW Implementation/ representation*	*Testing Method**
Steady-state vertical flow	correctness, accuracy	code function	verification
Steady-state horizontal flow	correctness, accuracy	code function	verification
Steady-state threedimensional flow	correctness, accuracy	code function	verification
Transient vertical flow	correctness, accuracy	code function	verification
Transient horizontal flow	correctness, accuracy	code function	verification
Transient radial flow	correctness, accuracy	code function	verification
Transient threedimensional flow	correctness, accuracy	code function	verification
Multiple parameter zones to represent heterogeneity	correctness	code function	verification, inter-comparison
Representing aquifer pinchout, aquitard pinchout, dipping beds, outcrops, subcrops, and unconformities	applicability	model construction	inter-comparison
Representing variable thickness layers	correctness, stability	code function	verification, inter-comparison
Storativity conversion in space and time. When the head in a section of a confined aquifer drops below the top of that aquifer in that area, conditions reverse to unconfined, and vice versa. Accordingly, the code needs to switch between confined storativity and unconfined storativity (specific yield).	correctness, accuracy, stability	code function	verification, inter-comparison
Horizontal anisotropy	correctness, accuracy	code function	verification

Functionality Issue	*Test Objective(s)*	*DYNFLOW Implementation/ representation*	*Testing Method**
Vertical anisotropy	correctness, accuracy	code function	verification, inter-comparison
Element-wise changing principal directions	correctness, accuracy	code function	inter-comparison
Unconfined flow. In an unconfined aquifer, transmissivity/conductance is a function of saturated thickness, and thus dependent on the computed heads.	correctness, accuracy, stability	code function	verification, inter-comparison, demonstration
Unconfined flow. In multi-layer models of unconfined aquifers, a rising water table might arise above the initial saturated/wetted model layers, invading dry cells (resaturation/wetting).	correctness, accuracy, stability	code function	inter-comparison, demonstration
Unconfined flow. In multi-layer models of unconfined aquifers, a falling water table might drop below the bottom of the initial (partially) water-filled cells (desaturation).	correctness, accuracy, stability	code function	inter-comparison, demonstration
Unconfined flow. A declining head may (non-) deliberately drop below the bottom of model domain.	correctness, stability	code function	consistency inspection
Internal no-flow areas and their (lack of) influence on results (heads, mass balance)	applicability, correctness	model formulation (grid design or parameter allocation)	inter-comparison
Sharp contrast in hydraulic conductivity of neighboring elements (lateral)	accuracy, stability	code function	inter-comparison, consistency inspection
Sharp contrast in hydraulic conductivity of neighboring layers	accuracy, stability	code function	inter-comparison, consistency inspection
Simulation of thin, conductive zones such as fracture zones and underdrains (see also superposition and 1D elements in Table 2A)	applicability	model construction	inter-comparison

Functionality Issue	*Test Objective(s)*	*DYNFLOW Implementation/ representation*	*Testing Method**
Simulation of thin barriers such as slurry walls and faults (see also superposition and 2D elements in Table 2A)	applicability	model construction	inter-comparison
Stress dependent properties (hydraulic conductivity, effective porosity, storativity, specific yield)	correctness, accuracy	code function	verification, inter-comparison

*) consistency inspection refers to visual inspection of results for physical and mathematical consistency.

Table 2-C. Functionality Issues for Boundary Conditions.

Functionality Issue	*Test Objective(s)*	*DYNFLOW Implementation/ representation*	*DYNFLOW Testing**
Default no-flow (lateral, upper/lower boundary)	correctness, accuracy	code function	verification
Prescribed head (steady-state, transient)	correctness, accuracy	code function	verification
Prescribed flux (steady-state, transient)	correctness, accuracy	code function	verification
Areal recharge in top active elements (steady-state, transient)	correctness, accuracy	code function	verification, inter-comparison
Induced infiltration from stream or sourcebed aquifer (head-dependent varying flux)	applicability	model construction	verification, inter-comparison
Induced infiltration from stream or sourcebed aquifer (head-independent constant flux)	applicability	model construction	verification, inter-comparison
Switching between induced infiltration (from stream) and exfiltration (towards stream)	applicability	model construction	inter-comparison, consistency inspection

Functionality Issue	*Test Objective(s)*	*DYNFLOW Implementation/ representation*	*DYNFLOW Testing*[*]
Drain boundary (no boundary condition if head is below drain level)	correctness	code function	inter-comparison, consistency inspection
Reservoir boundary (extent of surface water body in contact with ground-water varies over time; head-dependent flux)	applicability	model construction	inter-comparison
Model dries up (head locally declines below model bottom)	correctness error message	code function	inter-comparison, consistency inspection
No flow regions within model area (represented by inactive elements, zero h.c. elements, or excluding it from model domain by creating internal boundary)	applicability	model construction code function	inter-comparison, consistency inspection
Recharging/discharging wells	correctness, accuracy	code function	verification
Multi-aquifer wells (filter in multiple model layers)	correctness, accuracy	code function	verification, inter-comparison
Depth-limited evapotranspiration	correctness, accuracy	code function	verification, inter-comparison
Pond element	correctness accuracy	code function	verification, inter-comparison
Springs/seeps	applicability	model construction	verification, inter-comparison
Seepage face	applicability	model construction	verification, demonstration

*) consistency inspection refers to visual inspection of results for physical and mathematical consistency.

2.3. TESTS DISCUSSED IN DOCUMENTATION

The identified test issues should be evaluated through a well-chosen set of benchmark and inter- and intracomparison tests. The documentation of Version 5.18 of DYNFLOW includes ten verification tests using independent benchmarks (see Table 3 and Table 4). Some of the tests have been set up to facilitate code intracomparison (e.g., DFTC03). For a number of tests, multiple runs were made reflecting alternative implementation of the benchmark with DYNFLOW. To assess the accuracy of the documented tests, the tests have been run again as part of this evaluation; the results are summarized in Appendix B, test cases DFTC01-DFTC09. Some DYNFLOW reference materials mention additional test cases (Wetting Front, Spherical, and Recharge & ET). These test cases have not been evaluated as part of the first phase of this code evaluation project because they were not described in the documentation available during the project. However, they have been included in the second phase (see section 2.4). It should be noted that the testing of DYNFLOW focused on test issues related to functions explicitly represented in DYNFLOW by commands and input parameters. Issues related to model formulation and construction have not been evaluated as part of this code evaluation project. All tests were performed using the ICCG solver, unless mentioned otherwise. The ICCG solver appears to be the most universal solver available in DYNFLOW. Performance of other available DYNFLOW solvers has not been included in this report.

Table 3. Tests discussed in DYNFLOW Documentation of April 1994.

DYNFLOW Documentation		This Report	
Test No.	Name	Test No.	Name
1.	Linear	DFTC01	Linear 1-D Flow
2.	Dupuit	DFTC02	1-D Dupuit (Non-Linear) Flow
3.	Tank	DFTC03	Tank/Pond Drainage
4.	Theis	DFTC04	Theis Curves
5.	Hantush	DFTC05	Hantush Solution
6.	Consolidation	DFTC06	Consolidation
7.	Pond	see test DFTC03	
8.	Prickett	DFTC09	Confined-Unconfined Storage Conversion
9.	Seepage	DFTC07	Seepage Face
10.	Mound	DFTC08	Mound

Table 4: List of code tests and example applications presented in the DYNFLOW documentation, version April 1994.

Reference Number	Name	Description	Test Objective(s)	Type of Benchmark
DFTC01A	Linear	Steady-state, one-dimensional horizontal flow between two fully penetrating parallel drains in homogeneous confined aquifer	• horizontal confined flow under steady-state conditions in isotropic aquifer • fixed head b.c.	analytical solution
DFTC01B			• horizontal anisotropy • horizontal rotation of principle axes	intra-comparison (partial testing)
DFTC01C			• rotation of principle axes in vertical plane	intra-comparison (partial testing)
DFTC02	Dupuit	Steady-state, one-dimensional unconfined horizontal flow to a fully-penetrating parallel drains	• horizontal unconfined flow under steady-state conditions in isotropic aquifer • unconfined condition in a multi-layer system • fixed head b.c.	analytical solution
DFTC03A	Tank Drainage	Transient, one-dimensional uniform vertical flow (gravity drainage) under unconfined conditions	• vertical flow and position phreatic surface under transient conditions	analytical solution; intra-comparison
DFTC03B			• performance of 1D element	
DFTC03C			• performance of POND element	
DFTC04	Theis	Transient, radial horizontal flow to a fully-penetrating well in an infinite, isotropic, confined aquifer of constant thickness	• transient horizontal flow under confined conditions (head and flux) • discharging well • lateral fixed head b.c.	analytical solution
DFTC05	Hantush	Transient, radial horizontal flow to a fully-penetrating well in an infinite, isotropic, leaky-confined aquifer nodal flux.	• transient horizontal and vertical flow under confined conditions (DF is fully 3D) • lateral fixed head b.c. • upper boundary fixed head b.c. • discharging well	analytical solution
DFTC06	Consolidation	Transient, confined, one-dimensional vertical flow (free drainage) in aquifer subject to consolidation	• transient vertical flow under confined conditions (free drainage) • fixed head at lower boundary • stress-varying permeability and porosity	analytical solution

Reference Number	Name	Description	Test Objective(s)	Type of Benchmark
DFTC07	Seepage	Steady-state, phreatic, one-dimensional horizontal flow with a seepage face	• steady-state unconfined horizontal flow • rising water algorithm • fixed head lateral boundary conditions • seepage face	analytical solution
DFTC08	Mound	Steady-state, phreatic, one-dimensional horizontal flow between two drains with uniform recharge.	• steady-state horizontal unconfined flow • lateral fixed head boundary condition • areal recharge	analytical solution
DFTC09	Confined-Unconfined Conversion	Transient, horizontal radial flow towards pumping well in homogeneous, isotropic aquifer under mixed confined/unconfined conditions	• transient horizontal (radial) flow • well discharge function • unconfined/confined storage factor conversion • unconfined/confined piezometric surface	analytical solution

The documented tests are well-designed from a verification perspective. Although incompletely documented, they are addressing major (but not all) code functions. Reviewing for completeness of testing, it appears that a number of test issues were not addressed by the code authors. These outstanding issues include:

- fully threedimensional flow;
- effects of high contrast in parameter values for neighboring elements (both lateral and vertical);
- desaturation below model or aquifer bottom;
- recharge and evapotranspiration;
- seepage face and resaturation (wetting front);
- multi-layer wells;
- combinations of stresses (recharge plus wells plus ET); and
- transient boundary conditions and stresses.

2.4. ADDITIONAL TESTS

To address some of the test issues not discussed in the code documentation, five additional tests were run (see Table 5). All additional tests were performed using the ICCG solver, as was the case with the first set of tests. The results are summarized in Appendix B, test cases DFTC10-DFTC14.

Table 5. List of additional DYNFLOW code tests.

Reference Number	Name	Description	Test Objective(s)	Type of Benchmark
DFTC10	Rising/Falling Water Table	Transient flow in a multi-layer, rectangular isotropic, homogeneous, unconfined aquifer; flow starts after sudden rise of fixed head boundary condition at one side of the semi-infinite model domain.	• unconfined potentiometric surface calculation (correctness/accuracy) • (re-)wetting of dry elements by rising water table (correctness/stability)	analytical solution
DFTC11	Spherical Flow	Steady-state flow away from an injection well with an infinite small screen located in the center of a three-dimensional infinite domain; the recharge rate is held constant; the aquifer is isotropic, homogeneous and confined.	• fully three-dimensional steady-state flow under confined conditions (i.e., symmetrical flow) • fixed head condition at the lateral, top and bottom boundaries • recharging well with constant flux • mass balance calculations	analytical solution
DFTC12	Recharge and ET	Steady state horizontal uniform flow between two fully penetrating drains in an isotropic, homogeneous, unconfined aquifer with a horizontal impermeable base modified by recharge and evaporation.	• distributed recharge and evaporation algorithms and their additive use.	analytical solution for recharge; manual evaluation of global water balance and local evaporation.

Reference Number	Name	Description	Test Objective(s)	Type of Benchmark
DFTC13	Heterogeneity	Steady state confined flow towards a fully penetrating well in a dual transmissivity, isotropic aquifer of infinite extent with a horizontal impermeable base. The two transmissivity zones are separated by a straight vertical plane (the Y-Z plane).	• assignment of properties • correct representation of heterogeneity.	analytical solution
DFTC14	Anisotropy	Transient flow towards a fully penetrating pumping well with a constant discharge rate in an anisotropic, homogeneous, confined porous medium of infinite extent and constant thickness.	• transient horizontal flow under confined anisotropic conditions • effects of discharging well • influence of lateral fixed head boundary condition	analytical solution

3.0 CONCLUSIONS

This report concerns the testing and evaluation of the ground-water flow modeling code DYNFLOW (version: 5.18; release date: September 1994), developed by Camp Dresser & McKee, Cambridge, Massachusetts. The testing and evaluation of DYNFLOW was carried out in two phases: 1) execution and evaluation of the tests described in the code's documentation, and 2) additional testing of the code conform procedures outlined in ASTM Standard D-6025. After analyzing DYNFLOW's functionality, the completeness of the earlier performed tests was assessed, upon which additional testing requirements were formulated and executed. The results of the tests have been documented in Appendix B of this report. The issues listed in table 2A for runtime testing have been addressed during the execution of the test cases. There were no performance problems regarding these issues.

The set of fourteen tests are adequate to test DYNFLOW's internal functionality, that is, those functions that are represented by coded routines. The results of the tests show that, if model construction and parameterization is carefully handled, the DYNFLOW code performs satisfactory. The quality of the results is very dependent on spatial and temporal discretization, as is typical for numerical simulation codes. This means that in its application, DYNFLOW requires careful design of grid structure and selection of time step sequence, a notion recognized by the code authors as reflected by the attention given to these issues in the documentation.

4. REFERENCES

van der Heijde, P. K. M., and Kanzer, D. A. (1995) Ground-Water Model Testing: Systematic Evaluation and Testing of Code Functionality and Performance. Submitted to U.S. Environmental Protection Agency under CR-818719, International Ground Water Modeling Center, Golden, Colorado.

Appendix A: DYNFLOW FUNCTIONALITY TABLE

GROUND WATER MODEL FUNCTIONALITY DESCRIPTION

MODEL NAME: DYNFLOW
VERSION: 5.18
RELEASE DATE: SEPTEMBER 1996

AUTHOR(S):
INSTITUTION OF DEVELOPMENT: CAMP DRESSER & MCKEE

CONTACT ADDRESS:
PHONE:
FAX:

PROGRAM LANGUAGE: FORTRAN 77
COMPUTER PLATFORM(S): VARIOUS

LEGAL STATUS: PROPRIETARY
PREPROCESSING OPTIONS: DYNPLOT

POSTPROCESSING FACILITIES: DYNPLOT

MODEL TYPE

■ single phase saturated flow
☐ single phase unsaturated flow
☐ vapor flow/transport
☐ solute transport
☐ virus transport
☐ heat transport
☐ matrix deformation
☐ geochemical
☐ optimization
☐ groundwater and surface water hydraulics
☐ parameter ID saturated flow (inverse numerical)
☐ parameter ID unsaturated flow (analytical/ numerical)
☐ parameter ID solute transport (numerical)
☐ aquifer test analysis
☐ tracer test analysis
☐ flow of water and steam
☐ fresh/salt water interface
☐ twophase flow
threephase flow
☐ phase transfers
☐ chemical transformations
☐ biochemical transformations
☐ watershed runoff
☐ sediment transport
☐ surface water runoff
☐ stochastic simulation
☐ geostatistics
☐ multimedia exposure
☐ pre-/postprocessing
☐ expert system
☐ data base
☐ ranking/screening
☐ water budget
☐ heat budget
☐ chemical species mass balance

UNITS

☐ SI system
■ metric units
☐ US customary units
■ any consistent system
☐ user-defined

PRIMARY USE

☐ research
☐ education
■ general use
☐ site-dedicated
☐ policy-setting

GENERAL MODEL CHARACTERISTICS

Parameter discretization

- ☐ lumped
  - ☐ mass balance approach
  - ☐ transfer function(s)
- ■ distributed
- ■ deterministic
- ☐ stochastic

Spatial orientation

saturated flow

- ■ 1D horizontal
- ■ 1D vertical
- ■ 2D horizontal (areal)
- ■ 2D vertical (crossectional or profile)
- ☐ 2D axi-symmetric (horizontal flow only)
- ■ fully 3D
- ■ quasi-3D (layered; Dupuit approx.)
- ☐ 3D cylindrical or radial (flow defined in horizontal and vertical directions)

unsaturated flow

- ☐ 1D orizontal
- ☐ 1D vertical
- ☐ 2D horizontal
- ☐ 2D vertical
- ☐ 2D axi-symmetric
- ☐ fully 3D
- ☐ 3D cylindrical or radial

Restart capability - types of updates possible

- ■ dependent variables (e.g., head, concentration, temperature)
- ☐ fluxes
- ☐ velocities
- ■ parameter values
- ■ stress rates (pumping, recharge)
- ■ boundary conditions

Discretization in space

- ☐ no discretization
- ■ uniform grid spacing/regular mesh
- ■ variable grid spacing/irregular mesh
- ☐ movable grid (relocation of nodes during run)
- ☐ maximum number of nodes/cells/elements
  - ■ modifiable in source code (requires compilation)
  - ☐ modifiable through input
- ☐ maximum number of nodes (standard version):
- ☐ maximum number of cells/elements (standard version):

Possible cell shapes

- ■ 1D linear
- ☐ 1D curvilinear
- ■ 2D triangular
- ☐ 2D curved triangular
- ☐ 2D square
- ☐ 2D rectangular
- ☐ 2D quadrilateral
- ☐ 2D curved quadrilateral
- ☐ 2D polygon
- ☐ 2D cylindrical
- ☐ 3D cubic
- ☐ 3D rectangular block
- ■ 3D hexahedral (6 sides)
- ☐ 3D tetrahedral (4 sides)
- ☐ 3D spherical

FLOW SYSTEM CHARACTERIZATION

Saturated zone

Hydrogeologic zoning

- ■ confined
- ■ semi-confined (leaky-confined)
- ■ unconfined (phreatic)
- ■ hydrodynamic approach
- ☐ hydraulic approach (Dupuit-Forcheimer assumption for horizontal flow)
- ■ single aquifer
- ■ single aquifer/aquitard system
- ■ multiple aquifer/aquitard systems

  max. number of aquifers:
- ■ discontinuous aquifers (aquifer pinchout)
- ■ discontinuous aquitards (aquitard pinchout)
- ■ storativity conversion in space (confined-unconfined)
- ■ storativity conversion in time
- ■ aquitard storativity

Hydrogeologic medium

- ■ porous medium
- ☐ fractured impermeable rock (fracture system, fracture network)
- ■ discrete individual fractures
- ☐ equivalent fracture network approach
- ■ discrete fracture zones
- ■ dual porosity system (flow in fractures and optional in porous matrix, storage in porous matrix and exchange between fractures and porous matrix)
- ■ uniform hydraulic properties (hydraulic conductivity, storativity)
- ■ anisotropic hydraulic conductivity
- ■ nonuniform hydraulic properties (heterogeneous)
- ■ hydraulic properties stress-dependent

Flow characteristics

- ■ single fluid, water
- ☐ single fluid, vapor
- ☐ single fluid, NAPL
- ☐ air and water flow
- ☐ water and steam flow
- ☐ moving fresh water and stagnant salt water
- ☐ moving fresh water and salt water
- ☐ water and NAPL
- ☐ water, vapor and NAPL
- ■ incompressible fluid
- ☐ compressible fluid
- ☐ variable density
- ☐ variable viscosity
- ■ linear laminar flow (Darcian flow)
- ☐ non-Darcian flow
- ■ steady-state flow
- ■ transient (non-steady state) flow
- ■ dewatering (desaturation of cells)
- ☐ dewatering (variable transmissivity)
- ■ rewatering (resaturation of dry cells)
- ☐ delayed yield from storage

Boundary conditions

- ☐ infinite domain
- ☐ semi-infinite domain
- ■ regular bounded domain
- ■ irregular bounded domain
- ■ fixed head
- ■ prescribed time-varying head
- ■ zero flow (impermeable barrier)
- ■ fixed cross-boundary flux
- ■ prescribed time-varying cross-boundary flux
- ■ areal recharge:
  - ■ constant in space
  - ■ variable in space
  - ■ constant in time
  - ■ variable in time

Boundary conditions - continued

- ■ induced recharge from or discharge to a source bed aquifer or a stream in direct contact with ground water
  - ■ surface water stage constant in time
  - ■ surface water stage variable in time
  - ■ stream penetrating more than one aquifer
- ■ induced recharge from a stream not in direct contact with groundwater
- ■ evapotranspiration dependent on distance surface to water table
- ■ drains (gaining only)
- ■ free surface
- ☐ seepage face
- ■ springs, seeps

Sources/Sinks

- ■ point sources/sinks (recharging/pumping wells)
  - ■ constant flow rate
  - ■ variable flow rate
  - ☐ head-specified
  - ■ partially penetrating
  - ☐ well loss
  - ☐ block-to-radius correction
  - ☐ well-bore storage
  - ■ multi-layer well
- ■ line source/sinks (internal drains)
  - ■ constant flow rate
  - ■ variable flow rate
  - ☐ head-specified
- ☐ collector well (horizontal, radially extending screens)
- ☐ mine shafts (vertical)
  - ☐ water-filled
  - ☐ partially filled
- ☐ mine drifts, tunnel (horizontal)
  - ☐ water-filled
  - ☐ partially filled

Flow System Characteristics -- continued

Dependent variable(s)

- ■ head
- ☐ drawdown
- ☐ pressure
- ☐ suction
- ☐ potential
- ☐ moisture content
- ☐ stream function
- ☐ velocity

Solution methods - Flow

- ☐ analytical
  - ☐ single solution
  - ☐ superposition
  - ☐ method of images

- ☐ analytic element method
  - ☐ point sources/sinks
  - ☐ line sinks
  - ☐ ponds
  - ☐ uniform flow
  - ☐ rainfall
  - ☐ layering
  - ☐ inhomogeneities
  - ☐ doublets
  - ☐ leakage through confining beds

- ☐ Semi-analytical
  - ☐ continuous in time, discrete in space
  - ☐ continuous in space, discrete in time
  - ☐ approximate analytical solution

- ☐ Solving stochastic PDE's
  - ☐ Monte Carlo simulations
  - ☐ spectral methods
  - ☐ small perturbation expansion
  - ☐ self-consistent or renormalization technique

- ■ Numerical

Spatial approximation
- ☐ finite difference method
  - ☐ block-centered
  - ☐ node-centered
- ☐ integrated finite difference method
- ☐ boundary elements method
- ☐ particle tracking
- ☐ pathline integration
- ■ finite element method

Time-stepping scheme
- ■ fully implicit
- ☐ fully explicit
- ■ Crank-Nicholson

Matrix-solving technique
- ■ Iterative
  - ■ SIP
  - ☐ Gauss-Seidel (PSOR)
  - ☐ LSOR
  - ■ SSOR
  - ☐ BSOR
  - ☐ ADIP
  - ☐ Iterative ADIP (IADI)
  - ☐ Predictor-corrector
- ■ Direct
  - ■ Gauss elimination
  - ☐ Cholesky decomposition
  - ☐ Frontal method
  - ■ Doolittle
  - ☐ Thomas algorithm
- ☐ Point Jacobi

- ☐ Iterative methods for nonlinear equations
  - ☐ Picard method
  - ☐ Newton-Raphson method
  - ☐ Chord slope method

- ☐ Semi-iterative
  - ■ conjugate-gradient

Flow System Characteristics -- continued

Output Characteristics - Flow

Echo of input (in ASCII text format)
- ■ grid (nodal coordinates, cell size, element connectivity
- ■ initial heads/pressures/potentials
- ☐ initial moisture content/saturation
- ☐ soil parameters/function coefficients
- ■ aquifer parameters
- ■ boundary conditions
- ■ stresses (recharge, pumping)

Simulation results - form of output
- ☐ dependent variables in binary format
- ■ complete results in ASCII text format
- ■ spatial distribution of dependent variable for postprocessing
- ☐ time series of dependent variable for postprocessing
- ☐ direct screen display - text
- ☐ direct screen display - graphics
- ☐ direct hardcopy (printer)
- ☐ direct plot (pen-plotter)
- ☐ graphic vector file
- ☐ graphic bit map/pixel/raster file

Simulation results - type of output
- ■ head/pressure/potential
  - ■ areal values (table, contours)
  - ■ temporal series (table, x-t graphs)
- ☐ saturation/moisture content
  - ☐ areal values (table, contours)
  - ☐ temporal series (table, x-t graphs)
- ☐ head differential/drawdown
  - ☐ areal values (table, contours)
  - ☐ temporal series (table, x-t graphs)
- ☐ moisture content/saturation
  - ☐ areal values (table, contours)
  - ☐ temporal series (table, x-t graphs)

Type of output - continued
- ■ internal (cross-cell) fluxes
  - ■ areal values (table, vector plots)
  - ☐ temporal series (table, x-t graphs)
- ■ infiltration/recharge fluxes
  - ■ areal values (table, vector plots)
  - ☐ temporal series (table, x-t graphs)
- ■ evapo(transpi)ration fluxes
  - ■ areal values (table, vector plots)
  - ☐ temporal series (table, x-t graphs)
- ■ cross boundary fluxes
  - ■ areal values (table, vector plots)
  - ☐ temporal series (table, x-t graphs)
- ■ velocities
  - ■ areal values (table, vector plots)
  - ☐ temporal series (table, x-t graphs)
- ☐ stream function values
- ☐ streamlines/pathlines (graphics)
- ☐ traveltimes (tables)
- ☐ isochrones (graphics)
- ☐ position of interface (table, graphics)
- ☐ location of seepage faces
- ■ water budget components
  - ■ cell-by-cell
  - ■ global (total model area)
- ■ calculated parameters

Computational information
- ■ iteration progress
- ■ iteration error
- ■ mass balance error
- ☐ cpu time use
- ☐ memory allocation

Appendix B: GROUND-WATER FLOW TEST PROBLEMS

Test 1: LINEAR 1-D FLOW

Test 2: 1-D DUPUIT (NON-LINEAR) FLOW

Test 3: TANK/POND DRAINAGE

Test 4: THEIS CURVES

Test 5: HANTUSH SOLUTION

Test 6: CONSOLIDATION

Test 7: SEEPAGE FACE

Test 8: MOUND

Test 9: CONFINED-UNCONFINED STORAGE CONVERSION

Test 10: RISING/FALLING WATER TABLE (Wetting Front)

Test 11: SPHERICAL FLOW (Partial Penetrating Well in Confined Aquifer)

Test 12: RECHARGE AND ET

Test 13: HETEROGENEITY

Test 14: ANISOTROPY

Test 1: LINEAR

tests #:	DFTC01A, DFTC01B, DFTC01C
command files:	DFTC01A.CFI, DFTC01B.CFI, DFTC01C.CFI
grid files:	DFTC01A.GRF, DFTC01B.GRF, DFTC01C.GRF
output files:	DFTC01A.OUT, DFTC01B.OUT, DFTC01C.OUT
manual reference:	Section G-2
date of test execution:	October 28, 1996
title:	LINEAR: Horizontal one-dimensional confined (linear) flow
description:	Horizontal uniform flow between two fully penetrating drains in an isotropic, homogeneous, confined aquifer of uniform thickness and with horizontal impermeable base (see figure B1-1).

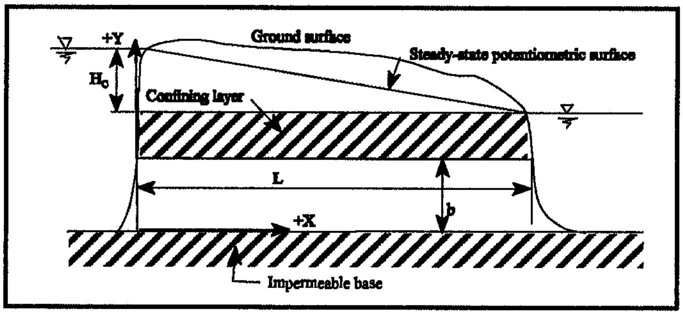


Figure B1-1. Conceptual model for test case DFTC01.

tested functions:	DFTC01A:	Confined potentiometric surface calculation and node point flux computations for case where principle direction of hydraulic conductivity is parallel with the flow direction; implementation of constant head boundary conditions.
	DFTC01B:	Horizontal anisotropy algorithm and rotation of principal direction of hydraulic conductivity in the horizontal plane.
	DFTC01C:	Rotation of principal direction of hydraulic conductivity in the vertical plane.
model domain:	Strip between two parallel drains with a length, width and thickness of L=100 ft, w=10 ft, and b=20 ft, respectively.	
boundary conditions:	Constant head at left boundary (x=0 ft) is h_o=100 ft; constant head at right boundary (x=100 ft) is h_L=50 ft; no-flow boundaries in y- and z-direction.	
benchmark:	Analytical solution for linear potentiometric surface between boundaries and flux calculations based on Darcy's law for confined, one-dimensional flow under steady-state	

conditions; discharge is calculated from:

$$Q=-KiA=-K\frac{H_c}{L}bw$$

where, Q = flow rate [L^3/T], K = hydraulic conductivity [L/T], i = hydraulic gradient [L/L], A = cross sectional area of flow [L^2], H_c = head at downstream boundary minus head at upstream boundary [L], L = length of aquifer [L], b = thickness of aquifer [L], and W = width of aquifer [L].

Hydraulic gradient over the length of the aquifer is constant at $i = 0.5$; flow rate in aquifer is constant at Q = 1,000 ft^3/d (i.e., inflow at upstream boundary, outflow at downstream boundary); heads are obtained by linear interpolation between given heads at the lateral (drain) boundaries.

grid: Two-dimensional horizontal grid with one layer and two levels; in plan view, the grid consists of 33 nodes in three rows, defining 40 elements (see figure B1-2). Heads are fixed above the layer to simulate confined conditions; note that the grid for test DFTC01C consist of 36 nodes and 44 elements.

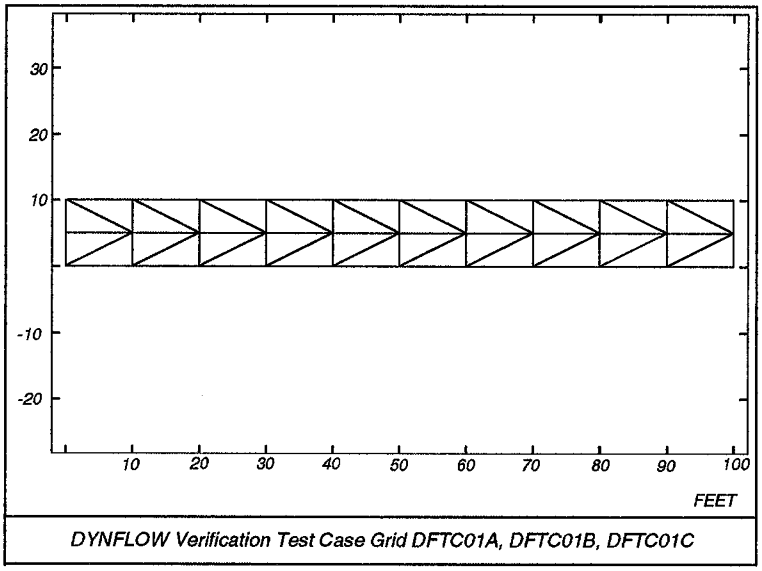


Figure B1-2. DYNFLOW grid for test case DFTC01.

initial conditions: n.a. (steady state)

time-stepping: n.a. (steady state)

system parameters: $K_x = K_y = K_z = 10.0$ ft/d

control parameters: Tolerance = .001 ft; alpha = 1.5 (relaxation factor); max. # outer iterations = 10; max. # inner iterations = 90

solver:	ICCG
test performed by:	Problem set up for numerical code prepared by code developers; code run and benchmark comparison performed by test report author.
type of comparison:	Graphic plot of heads in selected locations (see Fig. B1-3); tabular listing of heads (see Table B1-1); no statistical measures calculated in absence of non-zero deviations.

Table B1-1

distance from downstream end (ft)	piezometric head (ft)			
	analytical solution	DYNFLOW DFTC01A	DYNFLOW DFTC01B	DYNFLOW DFTC01C
0	50.	50.	50. (FH)	50. (FH)
10	55.	55.	55.	55.
20	60.	60.	60.	60.
30	65.	65.	65.	65.
40	70.	70.	70.	70.
50	75.	75.	75.	75.
60	80.	80.	80.	80.
70	85.	85.	85.	85.
80	90.	90.	90.	90.
90	95.	95.	95.	95.
100	100.	100.	100. (FH)	100. (FH)

FH - Fixed Head Node
(For all 3 test cases, level 1 results are identical to level 2 results)

Table B1-2

test case	DFTC01A	DFTC01B	DFTC01C
# of iterations	14	2	2
influx	1000.021 ft^3/d	1000.013 ft^3/d	499.994 ft^3/d
outflux	1000.006 ft^3/d	1000.012 ft^3/d	499.994 ft^3/d
total mass balance error	.0016%	1.0 E-4 %	0.0%

performance notes: Resulting heads for the three cases are identical to those for analytical solution (see Fig. B1-3). Flow rates for inflow (1000.021, 1000.013 and 499.994 ft^3/d, respectively) and outflow (1000.021, 1000.012, and 499.994 ft^3/d, respectively) match analytical results (1000.0, 1000.0, and 500.0 ft^3/d, respectively) very well.

DFTC01B - Results for heads are the same as in test DFTC01A, but with a smaller mass balance error; grid and principal direction of hydraulic conductivity have been rotated 45 degrees about the z-axis.

DFTC01C - Results for heads are the same as in test DFTC01A, but with a zero mass balance error; elevations and principal direction of hydraulic conductivity are rotated 45 degrees about the x-axis; grid horizontal and vertical distances are reduced by 0.70711 to produce the required flow distance.

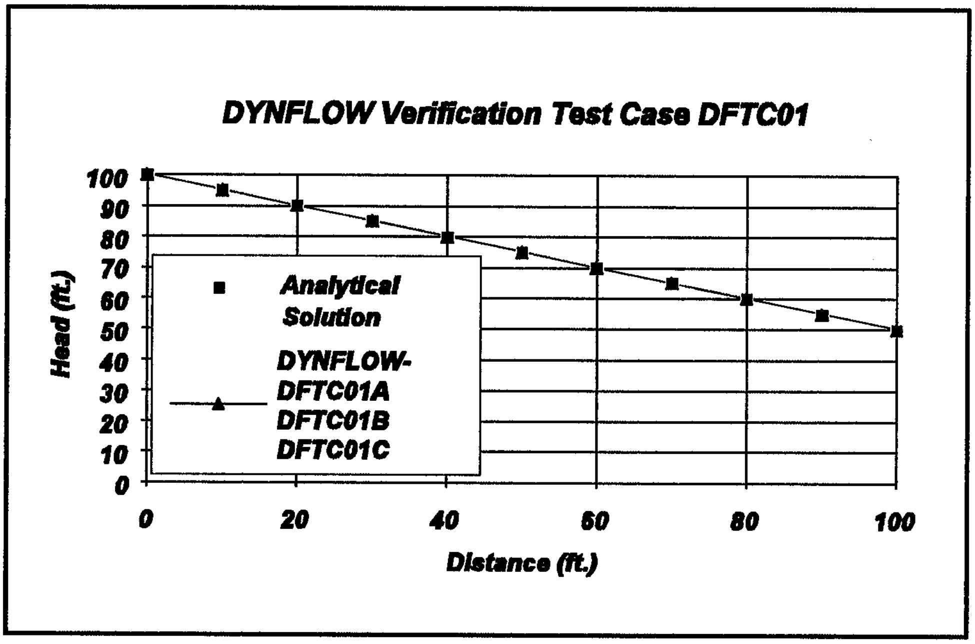


Figure B1-3. Head versus distance from origin (i.e., left boundary).

Command File DFTC01A.CFI

```
OUTPUT DFTC01A.OUT                          route outputs (head, iteration, balance to file
TITLE                                       indicates next three lines are simulation title
VERIFICATION CASE NO. 1A -- LINEAR STANDARD; RUN BY PVDH, BOULDER, CO.
LINEAR STEADY-STATE CONFINED 1D HORIZONTAL FLOW.
REF.:  ANY GW FLOW TEXTBOOK.
GRID READ DFTC01A.GRF FORM                  reads formatted (.GRF) grid information
LEVEL  2.                                   specifies number of vertical model levels
FREE                                        invokes specified flux (default) boundary conditions
PROP                                        defines aquifer properties as below
1,10.,10.,10.,0.,0.,0.,0.,0.                property set number, Kx (hydraulic conductivity in x
!                                           direction), Ky, Kz, storativity, specific yield,
```

```
!                                                         recharge/flux ,rotation about z, y axis (ccw)
ELEM  301                                                 selects element type computations, assigns property
!                                                         set numbers to elements; 3=three dimensional
!                                                         element  computations, 01=property set number
ELEV   0.   LEVELSING     1                               assigns elevations to node points (2 levels, 1 layer)
ELEV  20.   LEVELSING     2                               "
INIT 100.                                                 assigns initial heads to all nodes
INIT  50.   LEVELALL  NODE RANGE   31  33                 assigns initial heads to specific nodes
FIX         LEVELALL  NODE RANGE    1   3                 invokes specified head boundary conditions at nodes
FIX         LEVELALL  NODE RANGE   31  33                 "
DT    0.                                                  assigns simulation time step duration
TOL   0.001                                               assigns computation iteration tolerance
ITIN  90.                                                 sets max. number of inner loop iterations
ITER  30.                                                 sets max. number of outer loop iterations
ALPHA 1.5                                                 sets relaxation factor for internal iterations (D solver only)
NOPR                                                      supresses auto printing of tables
GOTIL  0.                                                 indicates steady state run
PRINT                                                     prints the summary of condition tables
SUMMARY                                                   prints property set assignment and mass balance tables
ERROR                                                     prints table of errors or warnings
! REPLACE NEXT WITH COMMAND 'END' IF YOU LIKE
XCFI                                                      returns control to interactive mode
```

Grid File DFTC01A.GRF

```
        33         40

         1          0       10.0
         2          0        5.0
         3          0          0
         4       10.0       10.0
         5       10.0        5.0
         6       10.0          0
         7       20.0       10.0
         8       20.0        5.0
         9       20.0          0
        10       30.0       10.0
        11       30.0        5.0
        12       30.0          0
        13       40.0       10.0
        14       40.0        5.0
        15       40.0          0
        16       50.0       10.0
        17       50.0        5.0
        18       50.0          0
        19       60.0       10.0
        20       60.0        5.0
        21       60.0          0
        22       70.0       10.0
        23       70.0        5.0
        24       70.0          0
        25       80.0       10.0
        26       80.0        5.0
        27       80.0          0
        28       90.0       10.0
        29       90.0        5.0
        30       90.0          0
        31      100.0       10.0
        32      100.0        5.0
        33      100.0          0

         1          5          4          1
         2          2          5          1
         3          3          5          2
         4          3          6          5
         5          8          7          4
         6          5          8          4
         7          6          8          5
         8          6          9          8
         9         11         10          7
        10          8         11          7
        11          9         11          8
        12          9         12         11
        13         14         13         10
        14         11         14         10
        15         12         14         11
        16         12         15         14
        17         17         16         13
        18         14         17         13
        19         15         17         14
        20         15         18         17
```

```
        21        20        19        16
        22        17        20        16
        23        18        20        17
        24        18        21        20
        25        23        22        19
        26        20        23        19
        27        21        23        20
        28        21        24        23
        29        26        25        22
        30        23        26        22
        31        24        26        23
        32        24        27        26
        33        29        28        25
        34        26        29        25
        35        27        29        26
        36        27        30        29
        37        32        31        28
        38        29        32        28
        39        30        32        29
        40        30        33        32
```

Command File DFTC01B.CFI

```
OUTPUT DFTC01B.OUT

TITLE
VERIFICATION CASE NO. 1B -- LINEAR HOR. ROTATED GRID; RUN BY PVDH, BOULDER, CO.
LINEAR STEADY-STATE CONFINED 1D HORIZONTAL FLOW.
REF.:  ANY GW FLOW TEXTBOOK.

TEXT
       THIS CASE IS THE SAME BASIC CASE AS CASE 1A EXCEPT
       THAT THE GRID IS ROTATED 45 DEGREES AND THE
       PRINCIPAL DIRECTION OF THE HYDRAILIC CONDUCTIVITY
       IS LIKEWISE ROTATED IN THE HORIZONTAL PLANE. THIS
       TESTS THE HORIZONTAL ANISOTROPY ALGORITHM - THE
       CALCULATED HEADS AND FLUX SHOULD BE THE SAME AS CASE 1A.
ENDT

GRID   READ DFTC01B.GRF    FORM             grid is rotated 45 degrees
LEVEL  2.
FREE
PROP
1,10.,0.,0.,0.,0.,0.,45.,0.                 parameter 8 ( rotates conductivity values ccw about the vertical axis)
ELEM        301
ELEV   0.   LEVELSING     1
ELEV  20.   LEVELSING     2
INIT 100.
INIT  50.   LEVELALL          NODE RANGE   31   33
FIX         LEVELALL          NODE RANGE    1    3
FIX         LEVELALL          NODE RANGE   31   33
DT     0.
TOL    0.001
ALPHA 1.5
ITIN   90.
ITER   30.
NOPR
GOTI  0.
PRINT
SUMMARY
ERROR
XCFI
```

Grid File DFTC01B.GRF

```
   33         40         5

    1     -7.071      7.071                                     1         5         4         1
    2     -3.535      3.535                                     2         2         5         1
    3      0.         0.                                        3         3         5         2
    4      0.        14.141                                     4         3         6         5
    5      3.535     10.606                                     5         8         7         4
    6      7.071      7.071                                     6         5         8         4
    7      7.071     21.212                                     7         6         8         5
    8     10.606     17.677                                     8         6         9         8
    9     14.141     14.141                                     9        11        10         7
   10     14.141     28.283                                    10         8        11         7
   11     17.677     24.749                                    11         9        11         8
   12     21.212     21.212                                    12         9        12        11
   13     21.212     35.355                                    13        14        13        10
   14     24.749     31.820                                    14        11        14        10
   15     28.282     28.282                                    15        12        14        11
   16     28.282     42.426                                    16        12        15        14
   17     31.820     38.891                                    17        17        16        13
   18     35.355     35.355                                    18        14        17        13
   19     35.355     49.497                                    19        15        17        14
   20     38.891     45.962                                    20        15        18        17
   21     42.426     42.426
   22     42.426     56.569
   23     45.962     53.033
   24     49.497     49.497
   25     49.497     63.640
   26     53.033     60.104
   27     56.569     56.569
   28     56.569     70.711
   29     60.104     67.175
   30     63.640     63.640
   31     63.640     77.782
   32     67.175     74.246
   33     70.711     70.711


   21         20        19        16
   22         17        20        16
   23         18        20        17
   24         18        21        20
   25         23        22        19
   26         20        23        19
   27         21        23        20
   28         21        24        23
   29         26        25        22
   30         23        26        22
   31         24        26        23
   32         24        27        26
   33         29        28        25
   34         26        29        25
   35         27        29        26
   36         27        30        29
   37         32        31        28
   38         29        32        28
   39         30        32        29
   40         30        33        32
```

Command File DFTC01C.CFI

```
OUTPUT  DFTC01C.OUT

TITLE
VERIFICATION CASE NO. 1C -- LINEAR VERT. ROTATED GRID; RUN BY PVDH, BOULDER, CO.
LINEAR STEADY-STATE CONFINED 1D HORIZONTAL FLOW.
REF.:  ANY GW FLOW TEXTBOOK.

TEXT
       THIS CASE IS THE SAME BASIC CASE AS CASE 1A EXCEPT
       THAT THE ELEVATIONS ARE ROTATED 45 DEGREES AND THE
       PRINCIPAL DIRECTION OF THE HYDRAULIC CONDUCTIVITY
       IS LIKEWISE ROTATED IN THE VERTICAL PLANE. THIS
       TESTS THE VERTICAL ANISOTROPY ALGORITHM - THE
       CALCULATED HEADS AND FLUX SHOULD BE THE SAME AS CASE 1A.
       NOTE THAT GRID IS EXPANDED BY ONE TIER OF ELEMENTS
       AND NODES AND THAT HORIZONTAL AND VERTICAL DISTANCES
       ARE REDUCED BY 0.70711 TO PRODUCE THE REQUIRED LENGTH
       OF 100 UNITS DIAGONALLY - ALSO THE THICKNESS NORMAL TO THE BEDDING
       IS NOW 10 UNITS AND THE HYDRAULIC CONDUCTIVITY IS 20 UNITS/TIME UNIT
       FOR THE SAME REASON.
ENDT
GRID   READ DFTC01C.GRF   FORM
LEVEL  2.
FREE
PROP
1,20.,0.,0.,0.,0.,0.,0.,-45.                parameter 9 rotates conductivity values ccw about the x-axis
ELEM       301
ELEV     0.     LEVELSING    1    NODE RANGE    1    3      grid elevations rotated 45 degrees
ELEV    -7.071  LEVELSING    1    NODE RANGE    4    6
ELEV   -14.142  LEVELSING    1    NODE RANGE    7    9
ELEV   -21.213  LEVELSING    1    NODE RANGE   10   12
ELEV   -28.284  LEVELSING    1    NODE RANGE   13   15
ELEV   -35.355  LEVELSING    1    NODE RANGE   16   18
ELEV   -42.426  LEVELSING    1    NODE RANGE   19   21
ELEV   -49.497  LEVELSING    1    NODE RANGE   22   24
ELEV   -56.569  LEVELSING    1    NODE RANGE   25   27
ELEV   -63.640  LEVELSING    1    NODE RANGE   28   30
ELEV   -70.711  LEVELSING    1    NODE RANGE   31   33
ELEV   -77.782  LEVELSING    1    NODE RANGE   34   36
ELEV            LEVELSING    1    SAVE DFTC01C.ELV
ELEV            LEVELSING    2    REXL DFTC01C.ELV
ELEV    7.071   LEVELSING    2    ADD
INIT   100.
INIT    50.     LEVELALL          NODE RANGE   31   36
FIX             LEVELALL          NODE RANGE    1    3
FIX             LEVELSING    2    NODE RANGE    4    6
FIX             LEVELALL          NODE RANGE   34   36
FIX             LEVELSING    1    NODE RANGE   31   33
DT     0.
TOL    0.001
ALPHA 1.5
ITIN   90.
ITER   30.
NOPR
GOTI   0.
PRINT
SUMMARY
ERROR
XCFI
```

Grid File DFTC01C.GRF

```
36        44

 1         0     10.0
 2         0      5.0
 3         0        0
 4     7.071     10.0
 5     7.071      5.0
 6     7.071        0
 7    14.142     10.0
 8    14.142      5.0
 9    14.142        0
10    21.213     10.0
11    21.213      5.0
12    21.213        0
13    28.284     10.0
14    28.284      5.0
15    28.284        0
16    35.355     10.0
17    35.355      5.0
18    35.355        0
19    42.426     10.0
20    42.426      5.0
21    42.426        0
22    49.497     10.0
23    49.497      5.0
24    49.497        0
25    56.569     10.0
26    56.569      5.0
27    56.569        0
28    63.640     10.0
29    63.640      5.0
30    63.640        0
31    70.711     10.0
32    70.711      5.0
33    70.711        0
34    77.782     10.0
35    77.782      5.0
36    77.782        0

 1         5        4        1
 2         2        5        1
 3         3        5        2
 4         3        6        5
 5         8        7        4
 6         5        8        4
 7         6        8        5
 8         6        9        8
 9        11       10        7
10         8       11        7
11         9       11        8
12         9       12       11
13        14       13       10
14        11       14       10
15        12       14       11
16        12       15       14
17        17       16       13
18        14       17       13
19        15       17       14
20        15       18       17
21        20       19       16
22        17       20       16
23        18       20       17
24        18       21       20
25        23       22       19
26        20       23       19
27        21       23       20
28        21       24       23
29        26       25       22
30        23       26       22
31        24       26       23
32        24       27       26
33        29       28       25
34        26       29       25
35        27       29       26
36        27       30       29
37        32       31       28
38        29       32       28
39        30       32       29
40        30       33       32
41        35       34       31
42        32       35       31
43        33       35       32
44        33       36       35
```

Test 2: 1-D NON-LINEAR FLOW

test #:	DFTC02 (DUPUIT)
input file:	DFTC02.CFI
grid file:	DFTC02.GRF
output file:	DFTC02.OUT
manual reference:	Section G-3
date of test execution:	October 1996
title:	DUPUIT: horizontal one-dimensional unconfined (non-linear) flow.
description:	Steady-state horizontal flow between two fully penetrating canals with different surface potentials in an isotropic, homogeneous, unconfined aquifer with a horizontal impermeable base (see figure B2-1).

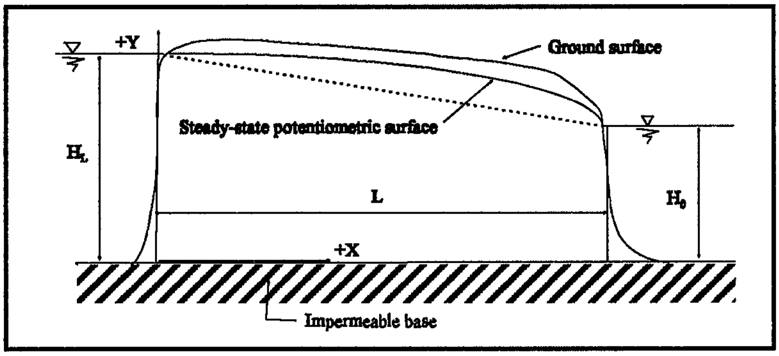


Fig. B2-1. Conceptual model for test case DFTC02.

tested functions:	Unconfined potentiometric surface calculation (across multiple layers) and node point flux computations for case where principle direction of hydraulic conductivity is parallel with the flow direction; implementation of constant head boundary conditions.
model domain:	Strip between two parallel drains with a length, and width of L=100 ft, and w=10 ft, respectively.
boundary conditions:	Constant head at left boundary (x=0 ft) is $h_o=100$ ft; constant head at right boundary (x=100 ft) is $h_L=50$ ft; no-flow boundaries in y- and z-direction.
benchmark:	Analytical solution for a nonlinear potentiometric surface between two fixed head boundaries in a unconfined aquifer under steady-state conditions as function of distance x from upper boundary; the solution is based on the Dupuit-Forcheimer assumption of fully horizontal flow (neglecting vertical flow in the unconfined aquifer, including near the outflow boundary):

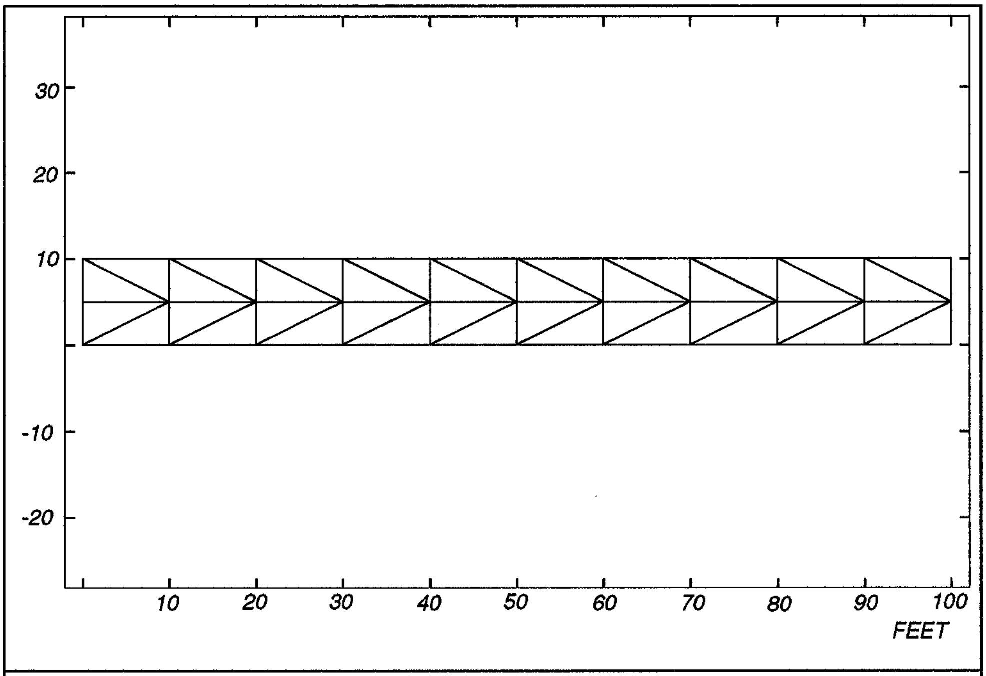
$$h^2=h_0^2-\frac{x}{L}(h_0^2-h_L^2)$$

and the discharge is calculated from:

$$Q=\frac{K}{2L}(h_0^2-h_L^2)\ bw$$

where, Q = flow rate [L^3/T], K = hydraulic conductivity [L/T], H_L = fixed head at downstream boundary [L], H_0 = fixed head at upstream boundary [L], L = length of aquifer [L], b = aquifer thickness, and w = width of aquifer [L].

grid: Grid with five layer and six levels (0, 20, 40, 60, 80, and 200 ft); in plan view, the grid consists of 33 nodes in three rows, defining 40 elements (see figure B2-2); the horizontal definition of the grid is identical to the one used in the LINEAR test problem; heads are fixed below the top level to simulate unconfined conditions.



DYNFLOW Verification Test Case Grid DFTC02

Figure B2-2.

initial conditions: n.a. (steady state)

time-stepping: n.a. (steady state)

system parameters: Hydraulic conductivity $K_x = K_y = K_z = 1.0$ ft/d; resulting Q=375.0 ft^3/d.

control parameters: Tolerance = .001 ft; alpha = 1.5 (relaxation factor); max. # outer iterations = 10; max. # inner iterations = 90.

solver: ICCG

test performed by: Problem set up for numerical code prepared by code developers; code run and benchmark comparison performed by test report author.

type of comparison: Graphic plot of heads (see Fig. B2-3); tabular listing of heads (see Table B2-1); no statistical measures calculated.

Table B2-1

distance from downstream end (ft)	piezometric head (ft)						
	analytical solution	DYNFLOW DFTC02					
		level 1	level 2	level 3	level 4	level 5	level 6
0	50.	50. (FH)	50. (FH)	50. (FH)	50. (FH)	50. (FH)	50. (FH)
10	57.01.	56.97	56.98	57.03	57.09	57.09	57.09
20	63.25	63.21	63.22	63.25	63.31	63.33	63.33
30	68.92	68.89	68.89	68.92	68.96	68.99	68.99
40	74.16	74.13	74.14	74.16	74.19	74.23	74.23
50	79.06	79.03	79.03	79.05	79.08	79.12	79.12
60	83.67	83.64	83.64	83.66	83.68	83.72	83.73
70	88.03	88.01	88.01	88.02	88.04	88.07	88.09
80	92.20	92.17	92.17	92.18	92.20	92.23	92.25
90	96.18	96.15	96.16	96.17	96.18	96.20	96.22
100	100.	100. (FH)	100. (FH)	100. (FH)	100. (FH)	100. (FH)	100. (FH)
maximum difference with benchmark per level [ft]		.04	.03	.02	.08	.08	.08
FH - Fixed Head Node (The numbers listed for each level are the average of three values)							

Table B2-2

test case	DFTC02
max # of iterations	22 (level 1)
influx	375.150 ft^3/d
outflux	375.165 ft^3/d
total mass balance error	.0040%
max. head difference	.08 ft

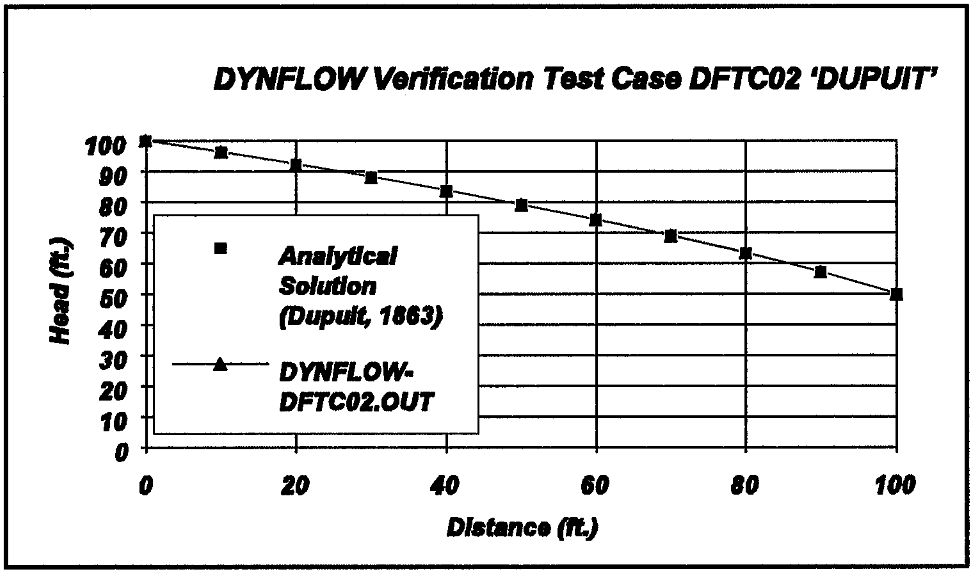


Figure B2-3. Heads versus distance from origin (i.e., left boundary).

performance notes: DFTC02 - Resulting heads differ slightly from the benchmark presented by the DYNFLOW authors (see Fig. B2-3). Computed flow rates for inflow and outflow differ about 0.04% from the analytical results (375.0 ft^3/d).

Command File DFTC02.CFI

```
OUTPUT DFTC02.OUT
!
TITLE
VERIFICATION CASE NO. 2 -- DUPUIT; RUN BY PVDH, BOULDER, CO.
DUPUIT STEADY-STATE UNCONFINED 1D HORIZ FLOW.
REF.: FREEZE AND CHERRY, "GROUNDWATER," PAGES 188-189.
!
TEXT

  H^2 = H0^2 - ( x / L )  ( H0^2 - H1^2 )

  Q   = ( k / ( 2  L ) )  ( H0^2 - H1^2 ) * w

  WHERE:

   H  = HEAD AT ANY POINT x.
   x  = DISTANCE FROM POINT 0 TO POINT L.
   0  = POINT MARKER FOR "LEFT" END OF AQUIFER.
   1  = POINT MARKER FOR "RIGHT" END OF AQUIFER.
   H0 = HEAD AT POINT 0.
   L  = LENGTH OF AQUIFER.
   H1 = HEAD AT POINT 1.
   k  = HYDRAULIC CONDUCTIVITY.
   ^2 = SQUARE.

  LET:

   H0 =  50.0
   H1 = 100.0
   L  = 100.0
   k  =   1.0
   w  =  10.0

  SOLUTION:

   H^2 = 2500 + 75  x

    x    H
   ---  ---
   10.  57.01
   20.  63.25
   30.  68.92
   40.  74.16
   50.  79.06
   60.  83.67
   70.  88.03
   80.  92.20
   90.  96.18

   Q   =   375.0

ENDT
!
GRID READ DFTC02.GRF FORM
LEVEL  6.
FREE
PROP
1,1.,1.,1.,0.,0.,0.,0.,0.
PROP
2,1.,1.,1.,0.,0.,0.
ELEM 301. &
     LAYERRANGE    1    3
ELEM 302.      LAYERRANGE    4    6
ELEV   0.      LEVELSING     1
ELEV  20.      LEVELSING     2
ELEV  40.      LEVELSING     3
```

```
ELEV  60.      LEVELSING     4
ELEV  80.      LEVELSING     5
ELEV 200.      LEVELSING     6
INIT 100.
INIT  50.      LEVELALL            NODE RANGE    1    3
```

Initial conditions set below top level to simulate unconfined conditions

```
FIX            LEVELALL            NODE RANGE    1    3
FIX            LEVELALL            NODE RANGE   31   33
DT     0.
ITIN  90.
ALPHA 1.5
ITER  30.
TOL   .001
NOPR
GOTIL 0.
PRINT
SUMMARY
ERROR

C000000000111111111122222222223333333333444444444455555555556666666666777777777778
C2345678901234567890123456789012345678901234567890123456789012345678901234567890

HEAD           LEVELSING     1     NODE &
 2, 5, 8, 11, 14, 17, 20, 23, 26, 29, 32, &
   SAVE DFTC02.CHK NOHD
FLFF SUM
SAVE DFTC02.SAV
END
```

Grid File DFTC02.GRF

```
        33        40

         1         0      10.0                                   18      50.0         0
         2         0       5.0                                   19      60.0      10.0
         3         0         0                                   20      60.0       5.0
         4      10.0      10.0                                   21      60.0         0
         5      10.0       5.0                                   22      70.0      10.0
         6      10.0         0                                   23      70.0       5.0
         7      20.0      10.0                                   24      70.0         0
         8      20.0       5.0                                   25      80.0      10.0
         9      20.0         0                                   26      80.0       5.0
        10      30.0      10.0                                   27      80.0         0
        11      30.0       5.0                                   28      90.0      10.0
        12      30.0         0                                   29      90.0       5.0
        13      40.0      10.0                                   30      90.0         0
        14      40.0       5.0                                   31     100.0      10.0
        15      40.0         0                                   32     100.0       5.0
        16      50.0      10.0                                   33     100.0         0
        17      50.0       5.0


         1         5         4         1
         2         2         5         1
         3         3         5         2
         4         3         6         5
         5         8         7         4
         6         5         8         4
         7         6         8         5
         8         6         9         8
         9        11        10         7
        10         8        11         7
        11         9        11         8
        12         9        12        11
```

```
      13        14        13        10
      14        11        14        10
      15        12        14        11
      16        12        15        14
      17        17        16        13
      18        14        17        13
      19        15        17        14
      20        15        18        17
      21        20        19        16
      22        17        20        16
      23        18        20        17
      24        18        21        20
      25        23        22        19
      26        20        23        19
      27        21        23        20
      28        21        24        23
      29        26        25        22
      30        23        26        22
      31        24        26        23
      32        24        27        26
      33        29        28        25
      34        26        29        25
      35        27        29        26
      36        27        30        29
      37        32        31        28
      38        29        32        28
      39        30        32        29
      40        30        33        32
```

Test 3: TANK/POND DRAINAGE

tests #:	DFTC03A, DFTC03B, DFTC03C
command files:	DFTC03A.CFI, DFTC03B.CFI, DFTC03C.CFI
grid files:	DFTC03A.GRF, DFTC03B.GRF, DFTC03C.GRF
output files:	DFTC03A.OUT, DFTC03B.OUT, DFTC03C.OUT
manual reference:	Section G-4
date of test execution:	October 1996
title:	POND: vertical one-dimensional transient flow
description:	A vertical tank or pond, initially full, is drained over time causing vertical flow in an isotropic, homogeneous, unconfined porous medium (see figure B3-1).

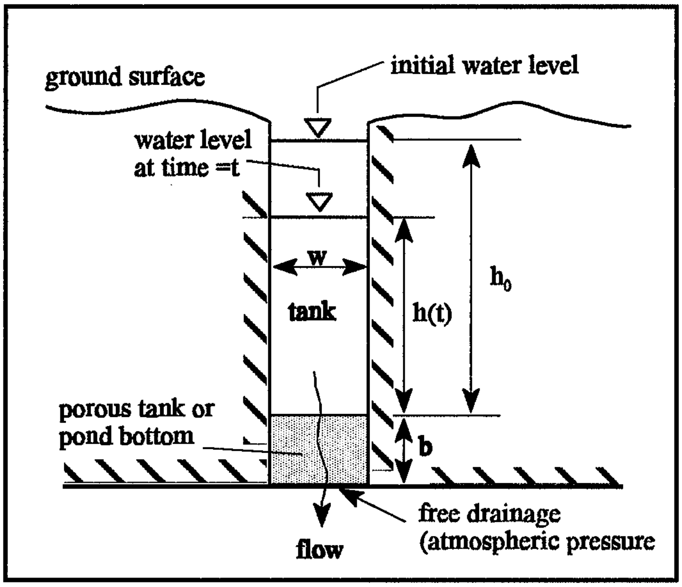


Figure B3-1. Conceptual model for test case DFTC03.

tested functions:	Vertical flow algorithms and unconfined potentiometric surface calculation under transient conditions (DFTC03A); functioning of 1D elements (DFTC03B), and operation of pond elements (DFTC03C).
model domain:	Porous strip of constant thickness between two parallel, vertical, impermeable walls with a length (perpendicular to drawing in Figure B3.1), width and thickness of L=10 ft, w=10 ft, and b=10 ft, respectively.

boundary conditions: Constant head at lower boundary (z=0 ft) is h_o=.001 ft representing atmospheric pressure; free surface at top boundary; no-flow boundaries in x- and y-direction; initial condition is set at $H_0 = 80$ ft.

benchmark: Analytical solution for head at the inflow point as function of time (derived by DYNFLOW authors):

$$h(t)=h_0\, e^{(-\frac{k}{b}t)}$$

and the discharge is calculated from:

$$Q = K\,\frac{h(t)}{b}\,Lw$$

where, Q = flow rate [L^3/T], K = hydraulic conductivity [L/T], L = length of porous section in y-direction [L], b = thickness of porous section, and w = width of porous section (in x-direction) [L].

grid: DFTC03A: grid with eight layers and nine levels, where the first 7 layers are 10 ft thick and the 8th layer (top layer) is 11 ft; in plan view, the grid consists of 4 nodes and 2 elements (see figure B3-2); the boundary condition at the top is represented by a series of cells with a decreasing water table.

DFTC03B: grid with eight layers and nine levels, where the first 7 layers are 10 ft thick and the 8th layer (top layer) is 11 ft; in plan view, the grid consists of 1 onedimensional element; the boundary condition at the top is represented by a series of cells with a decreasing water table.

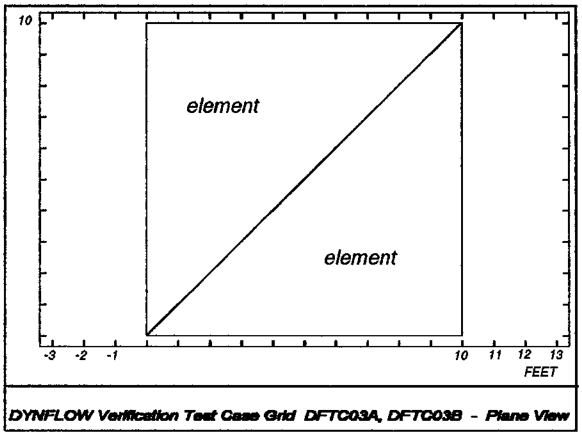


Figure B3-2.

DFTC03C: grid with one layer and two levels and a layer thickness of 10 ft; top boundary is represented by pond element; in plan view, the grid consists of 4 nodes and 2 elements (see figure B3-2).

initial conditions: h=80 ft

time-stepping: 10 time periods of 10 days; time steps of 1 day; to incorporate the initial condition, the first time period of 10 days has been divided in a large number of time steps of increasing size.

system parameters: Hydraulic conductivity $K_x = K_y = K_z = 0.1$ ft/d; specific storativity =0.0 and specific yield = 1.0.

control parameters: Tolerance = .0001 ft (DFTC03A/B), .001 (DFTC03C); alpha = 0.5 (relaxation factor); max. # outer iterations = 30; max. # inner iterations = 50

solver: ICCG (DFTC03A/B); GAUSS (DFTC03C); using ICCG solver in test case DFTC03C resulted in fatal error message: "ROUTINE ITCGIT - Q IS NOT POSITIVE DEFINITE"

test performed by: Problem set up for numerical code prepared by code developers; code run and benchmark comparison performed by test report author.

type of comparison: Graphic plot of heads (see Fig. B3-3); tabular listing of heads (see Table B3-1, B3-2 and B3-3); no statistical measures calculated.

Table B3-1

time (days)	piezometric head (ft)										
	analytical solution	inner (outer) iterations	DYNFLOW DFTC03A								
			1[1]	2	3	4	5	6	7	8	9
10	72.39	7(2)	.0	72.16	72.20	72.23	72.27	72.30	72.34	72.38	72.41
20	65.50	5(2)	.0	65.31	65.35	65.38	65.41	65.44	65.48	65.51	65.51
30	59.26	5(2)	.0	59.12	59.14	59.17	59.20	59.23	59.26	59.26	59.26
40	53.63	5(2)	.0	53.50	53.53	53.56	53.58	53.61	53.64	53.64	53.64
50	48.52	5(2)	.0	48.45	48.47	48.49	48.52	48.52	48.52	48.52	48.52
60	43.90	5(2)	.0	43.82	43.84	43.87	43.89	43.91	43.91	43.91	43.91
70	39.73	5(3)	.0	39.66	39.68	39.70	39.72	39.72	39.72	39.72	39.72
80	35.95	5(2)	.0	35.89	35.91	35.92	35.94	35.94	35.94	35.94	35.94
90	32.53	5(3)	.0	32.48	32.49	32.51	32.53	32.53	32.53	32.53	32.53
100	29.43	4(7)	.0	29.39	29.40	29.42	29.42	29.42	29.42	29.42	29.42
maximum difference with benchmark per level [ft]			.0	.23	.19	.16	.12	.09	.05	.01	.02

For each time, all values of the four nodes at each level are identical;
thus value listed is representative for particular level.
1) fixed head level

Table B3-2

	piezometric head (ft)		
		DYNFLOW1)	
time (days)	analytical solution	DFTC03B	DFTC03C
10	72.39	72.38 - 72.39	72.44
20	65.50	65.50	65.60
30	59.26	59.26-59.27	59.40
40	53.63	53.63	53.78
50	48.52	48.53	48.70
60	43.90	43.92	44.09
70	39.73	39.75	39.92
80	35.95	35.96	36.14
90	32.53	32.54	32.72
100	29.43	29.45	29.61
1) For each time, the range of values is given			

Table B3-3.

test case	Benchmark	DFTC03A	DFTC03B1)	DFTC03C1)
influx (at 100 days)	29.43 ft^3/d	29.464 ft^3/d	.297 ft^3/d	.297 ft^3/d
outflux (at 100 days)	29.43 ft^3/d	29.454 ft^3/d	.299 ft^3/d	.296 ft^3/d
total mass balance error (at 100 days)		.034%	.77%	.29%
1) Because case 3B is one-dimensional, multiply flux with cross-sectional area of 100 ft^2 to compare flux for case 3B with cases 3A and 3C.				

performance notes: DFTC03A - Although the resulting heads differ slightly from the benchmark presented by the DYNFLOW authors, especially in the early times, they are small and not visible in a graphic representation (see Fig. B3-3). Computed flow rates for inflow and outflow differ about 0.12% from the analytical results.

DFTC03B - The one-dimensional element approach is highly accurate with respect to heads, but has a larger mass balance error than the other cases, as well as a greater difference in flow rates with the benchmark (1%).

DFTC03C - There are some convergence problems using the pond element. The PCG solver did not run (see comment above) and the Gauss solver did not converge for a tolerance = 0.0001 as was used in the other cases; also, the 'SHOW' command for the POND function had to be commented out in the configuration file as this caused program abortion with an error message related to output format problems. The resulting heads differ slightly from the benchmark presented by the DYNFLOW authors (up to 0.6%), but are not large enough to be visible in a graphic representation (see Fig. B3-3). As is the case with DFTC03B, this case shows about 1% difference in external flux compared with the benchmark.

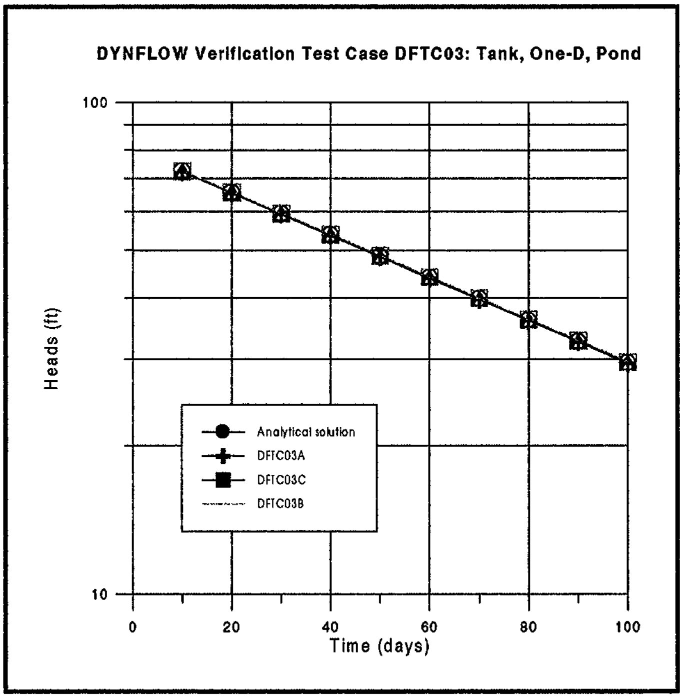


Figure B3-3.

Command File DFTC03A.CFI

```
OUTPUT DFTC03A.OUT
!
TITL
VERIFICATION CASE NO. 3 -- TANK; RUN BY PVDH, BOULDER, CO.
TANK TRANSIENT UNCONFINED 1D VERTICAL FLOW.
REF.:  ANY DIFFERENTIAL CALCULUS BOOK.
TEXT
  H(t) = H0  EXP( - ( k / b )  t )

  WHERE:

  H(t) = HEAD
  t    = TIME
  H0   = HEAD AT STARTING TIME
  EXP  = NATURAL EXPONENTIAL FUNCTION
  k    = VERTICAL HYDRAULIC CONDUCTIVITY
  b    = THICKNESS OF LOWER k ( LEAKY ) LAYER

  LET:

  H0 = 80.0
  k  =  0.1
  b  = 10.0

  SOLUTION:

            t    H(t)
           ---   ------
           10.   72.387
           20.   65.498
           30.   59.265
           40.   53.626
           50.   48.522
           60.   43.905
           70.   39.727
           80.   35.946
           90.   32.526
          100.   29.430

ENDT
!
GRID READ DFTC03A.GRF FORM
LEVEL  9.
FREE
ELEV   0.      LEVELSING     1
ELEV  10.      LEVELSING     2
ELEV  20.      LEVELSING     3
ELEV  30.      LEVELSING     4
ELEV  40.      LEVELSING     5
ELEV  50.      LEVELSING     6
ELEV  60.      LEVELSING     7
ELEV  70.      LEVELSING     8
ELEV  81.      LEVELSING     9
PROP
1, 1. , 1. , 0.1 , 0. , 1.0 , 0. , 0. ,0.
ELEM 301.      LAYERSING     1
PROP
2, 1. , 1. , 10000. , 0. , 1.0 , 0.
ELEM 302.      LAYERRANGE    2    8
INIT  80.
INIT   0.001   LEVELSING     1
FIX            LEVELSING     1
DT    .01
ITIN  50.
ALPHA 0.5
```

```
ITER  30.
TOL   0.0001
NOPR
HEAD          LEVELSING     9     NODE SING     1     SAVE DFTC3.TMP NOHD
GOTIL .01
PRINT
HEAD          LEVELSING     9     NODE SING     1     SAVE DFTC3.TMP NOHD
DT    .1
GOTIL .1
PRINT
HEAD          LEVELSING     9     NODE SING     1     SAVE DFTC3.TMP NOHD
GOTIL .5
PRINT
HEAD          LEVELSING     9     NODE SING     1     SAVE DFTC3.TMP NOHD
PRINT
DT    .1
GOTIL 1.
PRINT
HEAD          LEVELSING     9     NODE SING     1     SAVE DFTC3.TMP NOHD
GOTIL 2.
PRINT
HEAD          LEVELSING     9     NODE SING     1     SAVE DFTC3.TMP NOHD
DT    1.
GOTIL 5.
PRINT
HEAD          LEVELSING     9     NODE SING     1     SAVE DFTC3.TMP NOHD
GOTIL 10.
PRINT
C000000000111111111122222222223333333333444444444455555555556666666666777777777778
C234567890123456789012345678901234567890123456789012345678901234567890123456789 0
HEAD          LEVELSING     9     NODE SING     1     SAVE DFTC3.TMP NOHD
GOTIL 20.
PRINT
HEAD          LEVELSING     9     NODE SING     1     SAVE DFTC3.TMP NOHD
GOTIL 30.
PRINT
HEAD          LEVELSING     9     NODE SING     1     SAVE DFTC3.TMP NOHD
GOTIL 40.
PRINT
HEAD          LEVELSING     9     NODE SING     1     SAVE DFTC3.TMP NOHD
GOTIL 50.
PRINT
HEAD          LEVELSING     9     NODE SING     1     SAVE DFTC3.TMP NOHD
GOTIL 60.
PRINT
HEAD          LEVELSING     9     NODE SING     1     SAVE DFTC3.TMP NOHD
GOTIL 70.
PRINT
HEAD          LEVELSING     9     NODE SING     1     SAVE DFTC3.TMP NOHD
GOTIL 80.
PRINT
HEAD          LEVELSING     9     NODE SING     1     SAVE DFTC3.TMP NOHD
GOTIL 90.
PRINT
HEAD          LEVELSING     9     NODE SING     1     SAVE DFTC3.TMP NOHD
GOTIL 100.
HEAD          LEVELSING     9     NODE SING     1     SAVE DFTC3.TMP NOHD
PRINT
SUMM
ERROR
XCFI
```

Grid File DFTC03A.GRF

```
        4         2
        1       0.0        0.0
        2      10.0        0.0
        3      10.0       10.0
        4       0.0       10.0
        1         1          2         3
        2         1          3         4
```

Command File DFTC03B.CFI

```
OUTPUT DFTC03B.OUT
!
TITL
VERIFICATION CASE NO. 3B -- TANK, 1-DL ELEMENTS; RUN BY PVDH, BOULDER, CO.
TANK TRANSIENT UNCONFINED 1D VERTICAL FLOW.
REF.:  ANY DIFFERENTIAL CALCULUS BOOK.
TEXT

  H(t) = H0  EXP( - ( k / b )  t )

  WHERE:

  H(t) = HEAD
  t    = TIME
  H0   = HEAD AT STARTING TIME
  EXP  = NATURAL EXPONENTIAL FUNCTION
  k    = VERTICAL HYDRAULIC CONDUCTIVITY
  b    = THICKNESS OF LOWER k ( LEAKY ) LAYER

  LET:

  H0 = 80.0
  k  =  0.1
  b  = 10.0

  SOLUTION:

    t    H(t)
   ---  ------
   10.  72.387
   20.  65.498
   30.  59.265
   40.  53.626
   50.  48.522
   60.  43.905
   70.  39.727
   80.  35.946
   90.  32.526
  100.  29.430

ENDT
!
GRID READ DFTC03B.GRF FORM
LEVEL  9.
FREE
ELEV   0.      LEVELSING     1
ELEV  10.      LEVELSING     2
ELEV  20.      LEVELSING     3
ELEV  30.      LEVELSING     4
ELEV  40.      LEVELSING     5
```

```
ELEV  50.      LEVELSING     6
ELEV  60.      LEVELSING     7
ELEV  70.      LEVELSING     8
ELEV  81.      LEVELSING     9
PROP
11,0.1,0.1,0.1,0.,1.0,0.,0.,0.
ELEM 100.      LAYERSING     1
ONED   111.    LEVELRANGE    1    2NODE SING     1    1
PROP
12,10000.,10000.,10000.,0.,1.0,0.,0.,0.
ELEM 100.      LAYERRANGE    2    8
ONED   112.    LEVELRANGE    2    3NODE SING     1    1
ONED   112.    LEVELRANGE    3    4NODE SING     1    1
ONED   112.    LEVELRANGE    4    5NODE SING     1    1
ONED   112.    LEVELRANGE    5    6NODE SING     1    1
ONED   112.    LEVELRANGE    6    7NODE SING     1    1
ONED   112.    LEVELRANGE    7    8NODE SING     1    1
ONED   112.    LEVELRANGE    8    9NODE SING     1    1
INIT  80.
INIT   0.01    LEVELSING     1
FIX            LEVELSING     1
DT    .01
ITIN  50.
ALPHA 0.5
ITER  30.
TOL  0.0001
NOPR
HEAD           LEVELSING     9     NODE SING     1     SAVE DFTC3.TMP NOHD
GOTIL .01
HEAD           LEVELSING     9     NODE SING     1     SAVE DFTC3.TMP NOHD
DT    .02
GOTIL .1
HEAD           LEVELSING     9     NODE SING     1     SAVE DFTC3.TMP NOHD
GOTIL .5
HEAD           LEVELSING     9     NODE SING     1     SAVE DFTC3.TMP NOHD
DT    .1
GOTIL 1.
HEAD           LEVELSING     9     NODE SING     1     SAVE DFTC3.TMP NOHD
GOTIL 2.
HEAD           LEVELSING     9     NODE SING     1     SAVE DFTC3.TMP NOHD
DT    1.
GOTIL 5.
HEAD           LEVELSING     9     NODE SING     1     SAVE DFTC3.TMP NOHD
GOTIL 10.
PRINT
HEAD           LEVELSING     9     NODE SING     1     SAVE DFTC3.TMP NOHD
GOTIL 20.
PRINT
HEAD           LEVELSING     9     NODE SING     1     SAVE DFTC3.TMP NOHD
GOTIL 30.
PRINT
HEAD           LEVELSING     9     NODE SING     1     SAVE DFTC3.TMP NOHD
GOTIL 40.
PRINT
HEAD           LEVELSING     9     NODE SING     1     SAVE DFTC3.TMP NOHD
GOTIL 50.
PRINT
HEAD           LEVELSING     9     NODE SING     1     SAVE DFTC3.TMP NOHD
GOTIL 60.
PRINT
HEAD           LEVELSING     9     NODE SING     1     SAVE DFTC3.TMP NOHD
GOTIL 70.
PRINT
HEAD           LEVELSING     9     NODE SING     1     SAVE DFTC3.TMP NOHD
GOTIL 80.
PRINT
HEAD           LEVELSING     9     NODE SING     1     SAVE DFTC3.TMP NOHD
GOTIL 90.
PRINT
```

```
C000000000111111111122222222223333333333444444444455555555556666666666777777777778
C234567890123456789012345678901234567890123456789012345678901234567890123456789 0
HEAD           LEVELSING     9     NODE SING     1     SAVE DFTC3.TMP NOHD
GOTIL 100.
HEAD           LEVELSING     9     NODE SING     1     SAVE DFTC3.TMP NOHD
PRIN
SUMM
ERRO
XCFI
```

Grid File DFTC03B.GRF

```
         1         1
         1       0.0       0.0
         1         1         1          0
```

Command File DFTC03C.CFI

```
OUTPUT DFTC03C.OUT
!
TITLE
VERIFICATION CASE NO. 3C -- POND.
POND - SAME AS TANK, BUT USING POND ELEMENTS INSTEAD; RUN BY PVDH, BOULDER, CO.
REF.:  ANY DIFFERENTIAL CALCULUS BOOK.
TEXT

  H(t) = H0  EXP( - ( k / b )  t )

  WHERE:

  H(t) = HEAD
  t    = TIME
  H0   = HEAD AT STARTING TIME
  EXP  = NATURAL EXPONENTIAL FUNCTION
  k    = VERTICAL HYDRAULIC CONDUCTIVITY
  b    = THICKNESS OF LOWER k ( LEAKY ) LAYER

  LET:

  H0 = 80.0
  k  =  0.1
  b  = 10.0

  SOLUTION:

    t    H(t)
   ---   ------
   10.   72.387
   20.   65.498
   30.   59.265
   40.   53.626
   50.   48.522
   60.   43.905
   70.   39.727
   80.   35.946
   90.   32.526
  100.   29.430

ENDT
!
GRID READ DFTC03C.GRF FORM
LEVEL  2.
FREE
```

```
ELEV   0.      LEVELSING     1
ELEV  10.      LEVELSING     2
PROP
1,100.,100.,0.1,0.,1.0,0.,0.,0.
ELEM 301.
INIT   0.001   LEVELSING     1
INIT  80.      LEVELSING     2
FIX            LEVELSING     1
DT    10.
!
POND
NUMB
1
DATE
8,14,76,
CURV
3
10.,50.,100.,
0.,1.,1.,
0.,40.,90.,
PNOD
1,2,3,4,0
SPEC
70.0,0.0
!SHOW
ENDP
!
ITIN  50.
ALPHA 0.5
ITER  30.
TOL  0.001
NOPR
DT    0.01
HEAD           LEVELSING     2    NODE SING     1     SAVE DFTC3.TMP NOHD
GOTI   0.01
HEAD           LEVELSING     2    NODE SING     1     SAVE DFTC3.TMP NOHD
DT    .1
GOTIL .1
HEAD           LEVELSING     2    NODE SING     1     SAVE DFTC3.TMP NOHD
GOTIL .5
HEAD           LEVELSING     2    NODE SING     1     SAVE DFTC3.TMP NOHD
DT    .1
GOTIL 1.
HEAD           LEVELSING     2    NODE SING     1     SAVE DFTC3.TMP NOHD
GOTIL 2.
HEAD           LEVELSING     2    NODE SING     1     SAVE DFTC3.TMP NOHD
DT    1.
GOTIL 5.
HEAD           LEVELSING     2    NODE SING     1     SAVE DFTC3.TMP NOHD
GOTIL 10.
PRINT
HEAD           LEVELSING     2    NODE SING     1     SAVE DFTC3.TMP NOHD
GOTIL 20.
PRINT
HEAD           LEVELSING     2    NODE SING     1     SAVE DFTC3.TMP NOHD
GOTIL 30.
PRINT
HEAD           LEVELSING     2    NODE SING     1     SAVE DFTC3.TMP NOHD
GOTIL 40.
PRINT
HEAD           LEVELSING     2    NODE SING     1     SAVE DFTC3.TMP NOHD
GOTIL 50.
PRINT
HEAD           LEVELSING     2    NODE SING     1     SAVE DFTC3.TMP NOHD
GOTIL 60.
PRINT
HEAD           LEVELSING     2    NODE SING     1     SAVE DFTC3.TMP NOHD
GOTIL 70.
PRINT
```

```
HEAD          LEVELSING     2     NODE SING     1     SAVE DFTC3.TMP NOHD
GOTIL 80.
PRINT
HEAD          LEVELSING     2     NODE SING     1     SAVE DFTC3.TMP NOHD
C000000001111111111222222222233333333334444444444555555555566666666667777777778
C234567890123456789012345678901234567890123456789012345678901234567890123456789 0
GOTIL 90.
PRINT
HEAD          LEVELSING     2     NODE SING     1     SAVE DFTC3.TMP NOHD
GOTIL 100.
HEAD          LEVELSING     2     NODE SING     1     SAVE DFTC3.TMP NOHD
PRIN
SUMM
ERRO
XCFI
```

Grid File DFTC03C.GRF

```
         4         2
         1       0.0       0.0
         2       1.0       0.0
         3       1.0       1.0
         4       0.0       1.0
         1         1         2         3
         2         1         3         4
```

Test 4: THEIS CURVES

test #: DFTC04

command file: DFTC04.CFI

grid file: DFTC04.GRF

output file: DFTC04.OUT

manual reference: Section G-5

date of test execution: October 1996

title: THEIS: radial confined transient flow.

description: Transient flow towards a fully penetrating pumping well with a constant discharge rate in an isotropic, homogeneous, confined porous medium of infinite extent and constant thickness (see figure B4-1).

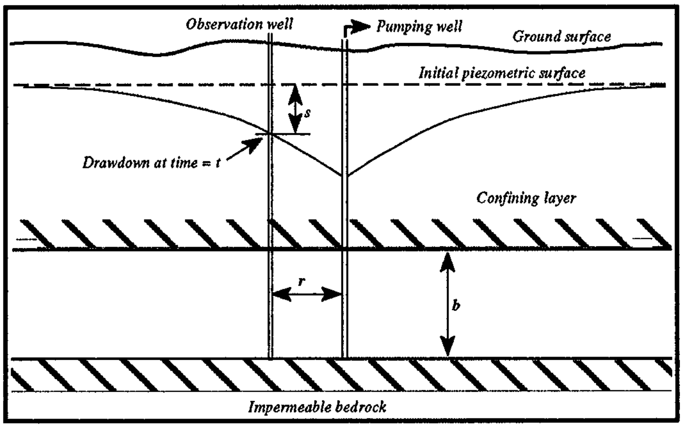


Figure B4-1.

tested functions: Transient horizontal flow under confined conditions; discharging well; lateral fixed head boundary condition.

model domain: Analytical solution: infinite horizontal extent, aquifer thickness b = 20 ft.

boundary conditions: Fixed head at outer radial boundary (R=11,900 ft) is h_R = 100 ft; well discharge rate Q = 160,000 ft^3/d is distributed as a specified flux boundary condition in the nodes located about 40 ft from the center of the quadrant (i.e., location of well in analytical solution); remaining boundary nodes are specified as no-flow boundaries.

benchmark: Theis analytical solution for drawdown with given transmissivity, storativity and pumping rate:

$$s = \frac{Q}{4\pi T} W(u)$$

where

$$u = \frac{r^2 S}{tT}$$

where, $\boldsymbol{Q}$ = flow rate [L^3/T], $\boldsymbol{T}$ = transmissivity [L^2/T] = $k_h\, b$, k_h = horizontal hydraulic conductivity of aquifer [L/T], $\boldsymbol{b}$ = thickness of aquifer [L], $\boldsymbol{S}$ = storativity [fraction], $\boldsymbol{r}$ = distance from well [L], $\boldsymbol{t}$ = time since start of pumping [T], $\boldsymbol{s}$ = drawdown with respect to prepumping horizontal piezometric surface [L], and $\boldsymbol{W}$ = the Theis Well Function [dimensionless]. Calculation are made for observation wells at r = 200, 650 and 1000 ft from the well, respectively.

grid: Single layer, 1/2-quadrant (45°) grid with two levels (see Figure B4-2); in plan view, the grid consists of 25 nodes defining 30 elements.

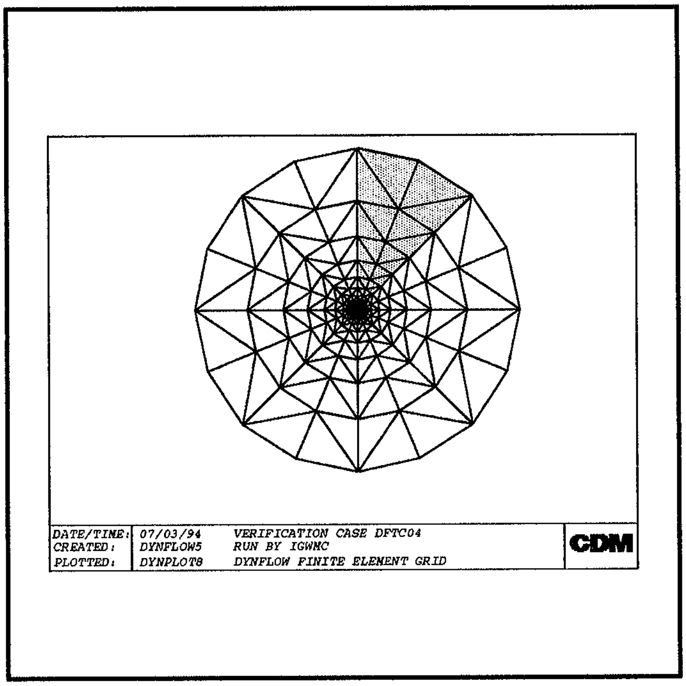


Figure B4-2.

initial conditions:	h=100 ft
time-stepping:	Preset time steps of 0.5 days, which is greater than the final time of computation; actual time step set such that each comparison time is a single time step from previous comparison time.
system parameters:	Hydraulic conductivity $k_x = k_y = K_h = 500$ ft/d, $k_z = 1$ ft/d; specific storativity = 0.00005 ft^{-1}; aquifer specific yield = 0.10.
control parameters:	Tolerance = .0001 ft; alpha = 1.5 (relaxation factor); acce = 1.5; max. # outer iterations = 30; max. # inner iterations = 90
solver:	ICCG
test performed by:	Problem set up for numerical code prepared by code developers; code run and benchmark comparison performed by test report author.
type of comparison:	Graphic plot of heads (see Fig. B4-3); tabular listing of heads (see Table B4-1, and B4-2; no statistical measures calculated.

Table B4-1.

		drawdown (ft)					
		r = 200 ft (node 4)		r = 650 ft (node 9)		r = 1000 ft(node 12)	
time (days)	# iterations	Theis	DF1)	Theis	DF1)	Theis	DF1)
t_1= 0.005	9	1.6	1.60-1.43	0.05	.09- .10	--	.01
t_2= 0.0125	9	2.65	2.92-2.75	0.36	.33	0.06	.06
t_3= 0.02375	10	3.4	3.52-3.38	0.78	.79- .80	0.25	.22
t_4= 0.040625	10	4.0	4.23-4.00	1.21	1.27-1.28	0.57	.53
t_5= 0.0659375	10	4.7	4.73-4.60	1.7	1.75	0.92	.89- .90
t_6= 0.1	11	5.2	5.28-5.12	2.2	2.19	1.3	1.26

1) For each time, the range of values from different levels is given, if applicable

Table B4-2. Global fluxes in ft^3/d

time step >	t_1	t_2	t_3	t_4	t_5	t_6
influx including storage	20000.06	20229.04	20023.72	20407.38	20086.71	20567.87
outflux	20005.44	20227.76	20030.75	20407.43	20090.15	20568.34
total mass balance error	.03%	.01%	.04%	.0003%	.02%	.002%

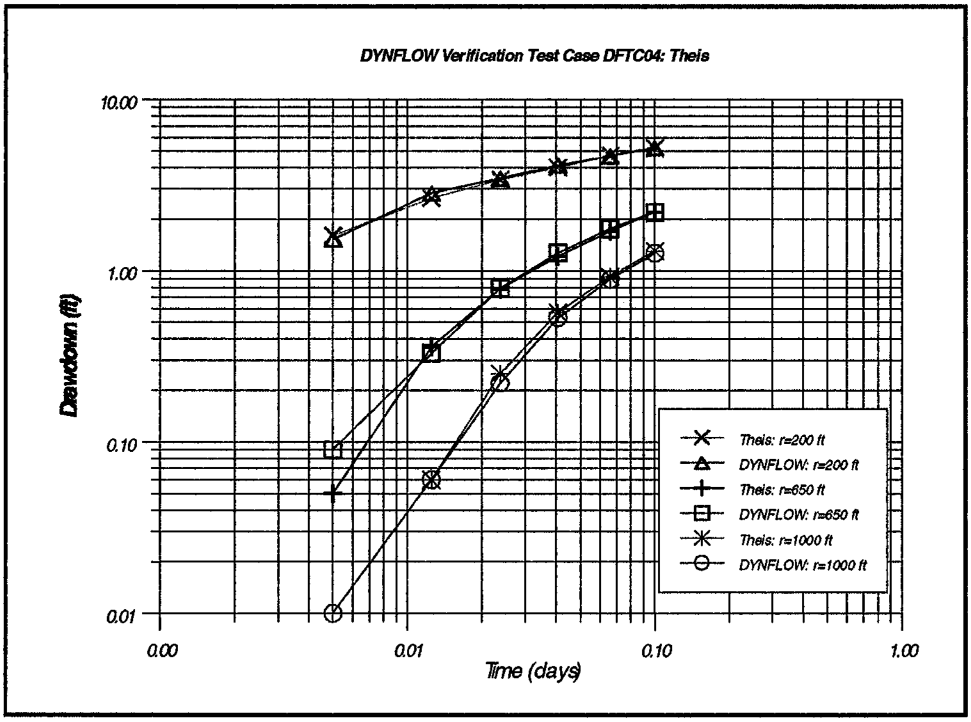


Figure B4-3.

performance notes: Although the resulting heads differ slightly from the benchmark presented by the DYNFLOW authors, especially in the early times, they are reasonably small. Mass balance error is very small for each of the time steps, although the flux varies slightly (note that pumping is constant).

Command File DFTC04.CFI

```
OUTPUT DFTC04.OUT
!
TITLE
VERIFICATION CASE NO. 4 -- THEIS; RUN BY PVDH, BOULDER, CO.
THEIS TRANSIENT PHREATIC AND CONFINED (MIXED) 2D
REF.:  LOHMAN, "GROUND-WATER HYDRAULICS," USGS PROF PAPER 708, PAGES 30-32.
TEXT

  LET:

  Kh = HORIZ HYDRAULIC CONDUCTIVITY
     =    500.
  Kv = VERT  HYDRAULIC CONDUCTIVITY
     = Kh
  b  = AQUIFER THICKNESS
     =     20.
  Ss = STORATIVITY
     =       0.00005
  Sy = SPECIFIC YIELD
     =       0.10
  Q  = WELL PUMPING RATE
     = 160,000.

  SOLUTION:

   OBTAIN IT BY USING THE PLATES GIVEN IN LOHMAN'S PAPER,
   WHICH FOR THREE POINTS IN AQUIFER IS AS FOLLOWS (APPX.):

  NODE POINT       4        9        12

  DISTANCE        200.     650.     1000.

    TIME              DRAWDOWN
   ------         -----  -----   -----
   .005           1.6    0.05    N/A
   .0125          2.65   0.36    0.06
   .02375         3.4    0.78    0.25
   .040625        4.0    1.21    0.57
   .0659375       4.7    1.7     0.92
   .1             5.2    2.2     1.3

ENDT
!
GRID READ DFTC04.GRF FORM
LEVEL  2.
FREE
ELEV   0.      LEVELSING     1
ELEV  20.      LEVELSING     2
PROP
1,500.,500.,1.,0.00005,0.10,0.,0.,0.
ELEM  301.
INIT  100.
FIX            LEVELALL            NODE RANGE   23   25
FLUX -5000.    LEVELALL            NODE RANGE    2    3
DT   0.005
TOL  .0001
ACCE 1.5
PRAL
ALPHA 1.5
ITIN  90.
C0000000011111111112222222222333333333344444444445555555555666666666677777777778
C2345678901234567890123456789012345678901234567890123456789012345678901234567890
ITER  30.
```

```
HEAD            LEVELSING     1      NODE SING     4      SAVE DFTC4.T4   NOHD
HEAD            LEVELSING     1      NODE SING     9      SAVE DFTC4.T9   NOHD
HEAD            LEVELSING     1      NODE SING    12      SAVE DFTC4.T12  NOHD
GOTIL .005
print
HEAD            LEVELSING     1      NODE SING     4      SAVE DFTC4.T4   NOHD
HEAD            LEVELSING     1      NODE SING     9      SAVE DFTC4.T9   NOHD
HEAD            LEVELSING     1      NODE SING    12      SAVE DFTC4.T12  NOHD
GOTIL .0125
print
HEAD            LEVELSING     1      NODE SING     4      SAVE DFTC4.T4   NOHD
HEAD            LEVELSING     1      NODE SING     9      SAVE DFTC4.T9   NOHD
HEAD            LEVELSING     1      NODE SING    12      SAVE DFTC4.T12  NOHD
GOTIL .02375
print
HEAD            LEVELSING     1      NODE SING     4      SAVE DFTC4.T4   NOHD
HEAD            LEVELSING     1      NODE SING     9      SAVE DFTC4.T9   NOHD
HEAD            LEVELSING     1      NODE SING    12      SAVE DFTC4.T12  NOHD
GOTIL .040625
print
HEAD            LEVELSING     1      NODE SING     4      SAVE DFTC4.T4   NOHD
HEAD            LEVELSING     1      NODE SING     9      SAVE DFTC4.T9   NOHD
HEAD            LEVELSING     1      NODE SING    12      SAVE DFTC4.T12  NOHD
GOTIL .0659375
print
HEAD            LEVELSING     1      NODE SING     4      SAVE DFTC4.T4   NOHD
HEAD            LEVELSING     1      NODE SING     9      SAVE DFTC4.T9   NOHD
HEAD            LEVELSING     1      NODE SING    12      SAVE DFTC4.T12  NOHD
GOTIL .1
print
HEAD            LEVELSING     1      NODE SING     4      SAVE DFTC4.T4   NOHD
HEAD            LEVELSING     1      NODE SING     9      SAVE DFTC4.T9   NOHD
HEAD            LEVELSING     1      NODE SING    12      SAVE DFTC4.T12  NOHD
XCFI
```

Grid File DFTC04.GRF

```
25        30

 1  -100.   0.
 2    -92.388   38.2683                            14 -1478.207  612.2935
 3    -92.388  -38.2683                            15    -1600.        0.
 4      -200.        0.                            16 -1478.207 -612.2935
 5 -323.3578  133.9392                             17 -2771.639 1148.0503
 6      -350.        0.                            18    -3000.        0.
 7 -323.3578 -133.9392                             19 -2771.639 -1148.050
 8 -600.5217  248.7442                             20 -5543.227 2296.1006
 9      -650.        0.                            21    -6000.        0.
10 -600.5217 -248.7442                             22 -5543.227 -2296.101
11    -923.88   382.683                            23 -11086.55 4592.2012
12     -1000.        0.                            24  -12000.        0.
13    -923.88  -382.683                            25 -11086.55 -4592.201

 1         1         2         4                   16        12        16        13
 2         1         4         3                   17        14        15        12
 3         2         5         4                   18        12        15        16
 4         3         4         7                   19        14        17        15
 5         5         6         4                   20        15        19        16
 6         4         6         7                   21        17        18        15
 7         5         8         6                   22        15        18        19
 8         6        10         7                   23        17        20        18
 9         8         9         6                   24        18        22        19
10         6         9        10                   25        20        21        18
11         8        11         9                   26        18        21        22
12         9        13        10                   27        20        23        21
13        11        12         9                   28        21        25        22
14         9        12        13                   29        23        24        21
15        11        14        12                   30        21        24        25
```

Test 5: HANTUSH SOLUTION

test #: DFTC05

command file: DFTC05.CFI

grid file: DFTC05.GRF

output file: DFTC05.OUT

date of test execution: October 1996

title: HANTUSH: radial leaky-confined transient flow

description: Transient flow towards a fully penetrating pumping well with a constant discharge rate in an isotropic, homogeneous, leaky-confined porous medium of infinite extent and constant thickness (see figure B5-1).

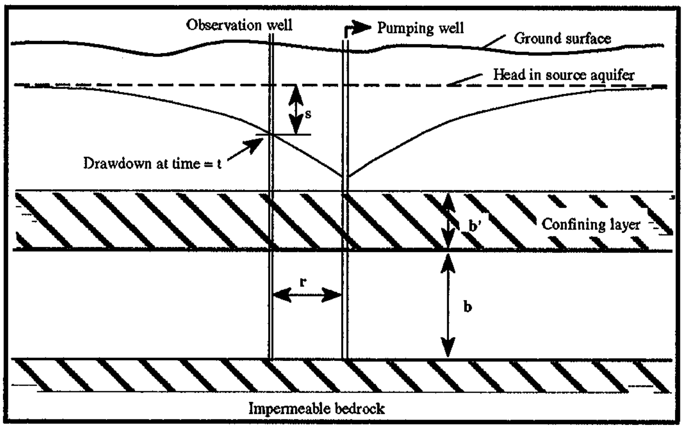


Figure B5-1.

tested functions: Transient horizontal and vertical flow under confined conditions; lateral and top fixed head boundary condition; discharging well.

model domain: Analytical solution: infinite horizontal extent, aquifer thickness b = 20 ft, aquitard thickness b' = 10 ft.

boundary conditions: Fixed head at outer radial boundary (R=11,900 ft) is h_R = 100 ft; well discharge rate Q = 160,000 ft^3/d is distributed as a specified flux boundary condition in the nodes located about 40 ft from the center of the quadrant (i.e., location of well in analytical solution); remaining boundary nodes are specified as no-flow boundaries.

benchmark: Hantush-Jacob (1955) analytical solution for drawdown with given transmissivity, storativity, leakance and pumping rate:

$$s=\frac{Q}{4\pi T}\,W(u,v)$$

where

$$u = \frac{r^2\,S}{tT}$$

and

$$v = \frac{r}{2}\sqrt{\frac{k'}{b'T}}$$

where, Q = flow rate [L^3/T], T = transmissivity [L^2/T] = $k_h\,b$, S = storativity [fraction], k_h = horizontal hydraulic conductivity of aquifer [L/T], b = thickness of aquifer [L], k' = vertical hydraulic conductivity of confining layer [L/T], b' = thickness of confining layer [L], r = distance from well [L], t = time since start of pumping [T], s = drawdown with respect to prepumping horizontal piezometric surface [L], and W = the Leakance Function [dimensionless]. Calculation are made for observation wells at r = 200, 650 and 1000 ft from the well, respectively.

grid: Single layer 1/2-quadrant (45°) grid (see Figure B5-2) with three levels at 0, 20, and 30 ft, respectively; in plan view, the grid consists of 25 nodes defining 30 elements.

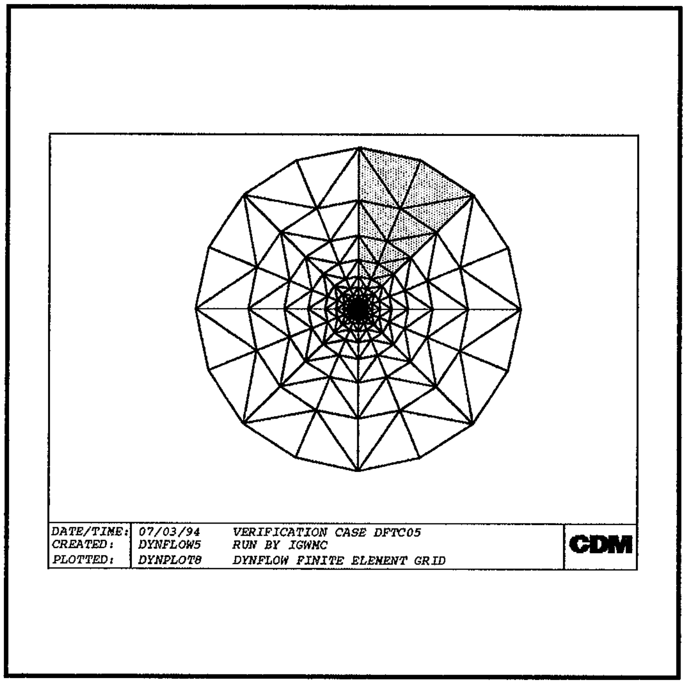


Figure B5-2.

initial conditions:	h=100 ft
time-stepping:	Preset time steps of 0.5 days, which is greater than the final time of computation; actual time step set such that each comparison time is a single time step from previous comparison time.
system parameters:	Hydraulic conductivity $k_x = k_y = k_h = 500$ ft/d, $k_z = 1$ ft/d; specific storativity = 0.00005 ft^{-1}; aquifer specific yield = 0.10; k' = 1.0 ft/d; specific storativity of aquitard was set at 0.00000001 ft^{-1} (a value of zero as suggested in the documentation caused a runtime error).
control parameters:	Tolerance = .0001 ft; alpha = 1.25 (relaxation factor); acce = 1.5; max. # outer iterations = 30; max. # inner iterations = 90.
solver:	ICCG
test performed by:	Problem set up for numerical code prepared by code developers; code run and benchmark comparison performed by test report author.
type of comparison:	Graphic plot of heads (see Fig. B5-3); tabular listing of heads (see Table B5-1, and B5-2; no statistical measures calculated.

Table B5-1.

		drawdown (ft)					
		r = 200 ft (node 4)		r = 650 ft (node 9)		r = 1000 ft(node 12)	
time (days)	# iterations	Hantush	DF[1)]	Hantush	DF[1)]	Hantush	DF[1)]
t_1= 0.005	8	1.246	1.18	0.041	.05	0.001	0
t_2= 0.0125	9	1.700	1.96 - 1.97	0.174	.14	0.026	.02
t_3= 0.02375	9	1.840	1.95 - 1.96	0.254	.25	0.058	.05
t_4= 0.040625	9	1.872	2.05 - 2.06	0.280	.26	0.073	.07
t_5= 0.0659375	9	1.876	1.99	0.285	.26	0.076	.06
t_6= 0.1	9	1.876	2.04 - 2.05	0.285	.26	0.076	.07
1) For each time, the range of values at different levels is given, if applicable							

Table B5-2. Global fluxes in ft^3/d

time step >	t_1	t_2	t_3	t_4	t_5	t_6
influx including storage	20006.770	21094.440	21078.300	21146.030	20998.310	20857.220
outflux	20004.710	21093.170	21083.340	21146.380	20997.910	20859.160
total mass balance error	.01%	.01%	.02%	.001%	.002%	.01%

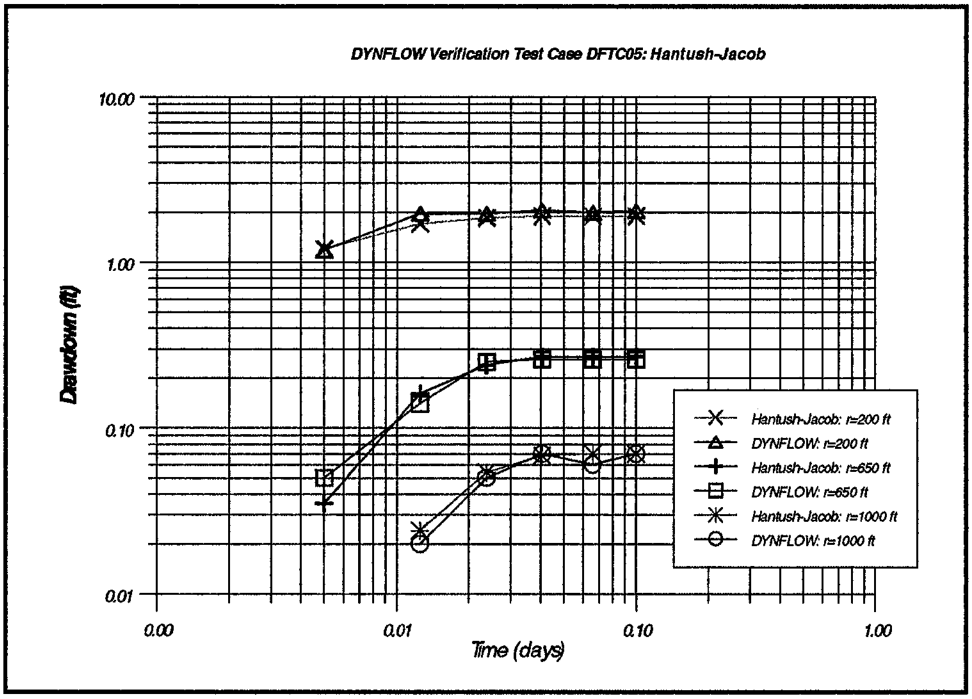


Figure B5-3.

performance notes: Although the resulting heads differ somewhat from the benchmark, they are reasonably small. The mass balance error is very small for each of the time steps, although the flux varies slightly (note that pumping is constant).

Command File DFTC05.CFI

```
OUTPUT DFTC05.OUT
!
TITLE
VERIFICATION CASE NO. 5 -- HANTUSH; RUN BY PVDH, BOULDER, CO.
HANTU TRANSIENT CONFINED 2D RADIAL HORIZ FLOW WITH LEAKAGE.
REF.:  LOHMAN, "GROUND-WATER HYDRAULICS," USGS PROF PAPER 708, PAGES 8.
TEXT

  LET:

  Kh = HORIZ HYDRAULIC CONDUCTIVITY
     =    500.
  Kv = VERT  HYDRAULIC CONDUCTIVITY
     = K' = 1.0
  b  = AQUIFER THICKNESS
     =     20.
  b' = AQUITARD THICKNESS
     =     10.
  Ss = SPECIFIC STORATIVITY
     =      0.00005
  Q  = WELL PUMPING RATE
     = 160000.

  SOLUTION:

   OBTAIN IT BY USING THE PLATES GIVEN IN LOHMAN'S PAPER,
   WHICH FOR THREE POINTS IN AQUIFER IS AS FOLLOWS (APPX.):

  NODE POINT         4        9        12
  DISTANCE          200.     650.     1000.
  NU PARAMETER      0.316    1.03      1.60

    TIME              DRAWDOWN
   ------       -----   -----   -----
   .005         1.2     0.035   N/A
   .0125        1.7     0.16    0.024
   .02375       1.85    0.24    0.054
   .040625      1.9     0.27    0.068
   .0659375     1.9     0.27    0.07
   .1           1.9     0.27    0.07

ENDT
GRID READ DFTC05.GRF FORM
LEVEL  3.
FREE
ELEV   0.      LEVELSING     1
ELEV  20.      LEVELSING     2
ELEV  30.      LEVELSING     3
PROP
1,500.,500.,500.,0.00005,0.0,0.,0.,0.
ELEM  301.     LAYERSING     1
PROP
2,1.,1.,1.,0.00000001,0.,0.,0.,0.
ELEM  302.     LAYERSING     2
INIT  100.
FIX            LEVELRANGE    1    2NODE RANGE   23   25
FIX            LEVELSING     3
FLUX -10000.   LEVELRANGE    1    2NODE SING     1
DT   0.005
TOL  .0001
ACCE  1.5
PRAL
ALPHA 1.25
ITIN  90.
ITER  30.
HEAD           LEVELSING     1     NODE SING     4     SAVE DFTC4.T4  NOHD
```

```
HEAD           LEVELSING    1     NODE SING    9     SAVE DFTC4.T9  NOHD
HEAD           LEVELSING    1     NODE SING   12     SAVE DFTC4.T12 NOHD
GOTIL .005
HEAD           LEVELSING    1     NODE SING    4     SAVE DFTC4.T4  NOHD
HEAD           LEVELSING    1     NODE SING    9     SAVE DFTC4.T9  NOHD
HEAD           LEVELSING    1     NODE SING   12     SAVE DFTC4.T12 NOHD
GOTIL .0125
HEAD           LEVELSING    1     NODE SING    4     SAVE DFTC4.T4  NOHD
HEAD           LEVELSING    1     NODE SING    9     SAVE DFTC4.T9  NOHD
HEAD           LEVELSING    1     NODE SING   12     SAVE DFTC4.T12 NOHD
GOTIL .02375
HEAD           LEVELSING    1     NODE SING    4     SAVE DFTC4.T4  NOHD
HEAD           LEVELSING    1     NODE SING    9     SAVE DFTC4.T9  NOHD
HEAD           LEVELSING    1     NODE SING   12     SAVE DFTC4.T12 NOHD
GOTIL .040625
HEAD           LEVELSING    1     NODE SING    4     SAVE DFTC4.T4  NOHD
HEAD           LEVELSING    1     NODE SING    9     SAVE DFTC4.T9  NOHD
HEAD           LEVELSING    1     NODE SING   12     SAVE DFTC4.T12 NOHD
GOTIL .0659375
HEAD           LEVELSING    1     NODE SING    4     SAVE DFTC4.T4  NOHD
HEAD           LEVELSING    1     NODE SING    9     SAVE DFTC4.T9  NOHD
HEAD           LEVELSING    1     NODE SING   12     SAVE DFTC4.T12 NOHD
GOTIL .1
HEAD           LEVELSING    1     NODE SING    4     SAVE DFTC4.T4  NOHD
HEAD           LEVELSING    1     NODE SING    9     SAVE DFTC4.T9  NOHD
HEAD           LEVELSING    1     NODE SING   12     SAVE DFTC4.T12 NOHD
XCFI
```

Grid File DFTC05.GRF

```
   25         30

    1  -100.    0.
    2    -92.388    38.2683                              15     -1600.         0.
    3    -92.388   -38.2683                              16 -1478.207 -612.2935
    4      -200.         0.                              17 -2771.639 1148.0503
    5 -323.3578   133.9392                               18     -3000.         0.
    6      -350.         0.                              19 -2771.639 -1148.050
    7 -323.3578  -133.9392                               20 -5543.227 2296.1006
    8 -600.5217   248.7442                               21     -6000.         0.
    9      -650.         0.                              22 -5543.227 -2296.101
   10 -600.5217  -248.7442                               23 -11086.55 4592.2012
   11   -923.88    382.683                               24  -12000.          0.
   12    -1000.         0.                               25 -11086.55 -4592.201
   13   -923.88   -382.683
   14 -1478.207   612.2935

    1          1          2          4                   17         14         15         12
    2          1          4          3                   18         12         15         16
    3          2          5          4                   19         14         17         15
    4          3          4          7                   20         15         19         16
    5          5          6          4                   21         17         18         15
    6          4          6          7                   22         15         18         19
    7          5          8          6                   23         17         20         18
    8          6         10          7                   24         18         22         19
    9          8          9          6                   25         20         21         18
   10          6          9         10                   26         18         21         22
   11          8         11          9                   27         20         23         21
   12          9         13         10                   28         21         25         22
   13         11         12          9                   29         23         24         21
   14          9         12         13                   30         21         24         25
   15         11         14         12
   16         12         16         13
```

Test 6: ONE-DIMENSIONAL CONSOLIDATION

test #: DFTC06A, DFTC06B

command file: DFTC06A.CFI, DFTC06B.CFI

grid file: DFTC06.GRF

output file: DFTC06A.OUT, DFTC06B.OUT

date of test execution: November 1996

title: One-dimensional flow through consolidating aquitard.

description: Transient vertical flow (free drainage) through a consolidating aquitard due to a falling water level on top; aquitard is isotropic and homogeneous (see figure B6-1).

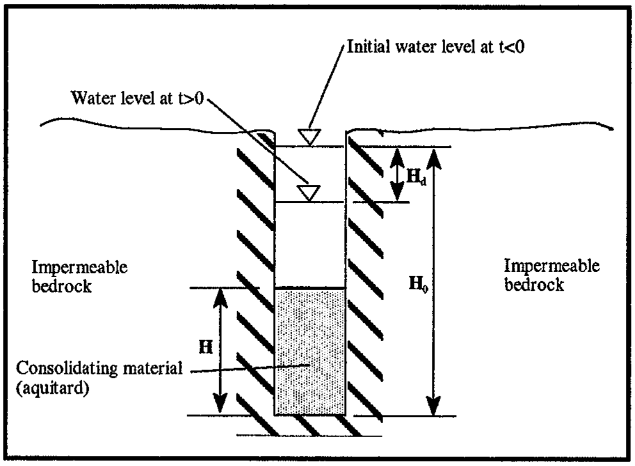


Figure B6-1.

tested functions: Transient vertical flow (free drainage); stress-dependent parameters (permeability, porosity), fixed head at lower boundary.

model domain: Column with length H = 100 ft (aquitard thickness) and unit width (in both X- and Y-direction) = 1 ft.

boundary conditions: Lateral no-flow condition; fixed head at bottom = 150 ft (representing head drop $H_d = 50$ ft).

benchmark: Graphic representation of Lambe and Whitman, tabularized by DYNFLOW authors.

grid: Two-element (4 nodes) in plan view; eight layers (see Figure B3-2) with levels at 0, 12.5, 25.0, 37.5, 50.0, 62.5, 75.0, 87.5, and 100.0 ft, respectively.

initial conditions: $H_0 = 200$ ft

time-stepping:	Preset time steps of 200 days (DFTC06A) and 100 days (DFTC06B) over a period of 9,000 days.
system parameters:	Hydraulic conductivity $k_x = k_y = k_h = 1.0$ ft/d, $k_z = 1.0$ ft/d; specific storativity = 1.0 ft^{-1}; aquifer specific yield = 1.0.
control parameters:	Tolerance = .001 ft; alpha = 1.8 (relaxation factor); acce = (not given); max. # outer iterations = 30; max. # inner iterations = 50.
solver:	ICCG
test performed by:	Problem set up for numerical code prepared by code developers; code run and benchmark comparison performed by test report author.
type of comparison:	Graphic plot of heads (see Fig. B6-3); tabular listing of heads (see Table B6-1, and B6-2; no statistical measures calculated.

Table B6-1.

time (days)	# iterations	head (ft) level 5 (1/4 point of leaky layer) benchmark	level 5 DF Δ t = 200 days	level 5 DF Δ t = 100 days	level 9 (midpoint of leaky layer) benchmark	level 9 DF Δ t = 200 days	level 9 DF Δ t = 100 days
1000	20	187.0	186.68	186.58	197.2	197.37	197.41
2000	20	177.5	177.56	177.53	188.5	188.52	188.49
3000	20	170.3	171.41	171.39	180.0	180.23	180.21
4000	20	166.7	166.71	166.71	173.7	173.63	173.61
5000	20	162.7	163.05	163.04	168.5	168.45	168.44
6000	20	160.0	160.19	160.18	164.3	164.41	164.40
7000	20	157.7	157.96	157.95	161.2	161.25	161.24
8000	20	155.8	156.21	156.21	158.8	158.78	158.78
9000	20	154.6	154.85	154.84	156.8	156.86	156.85

performance notes:	Although the resulting heads differ somewhat from the benchmark presented by the DYNFLOW authors, they are reasonably small (max 1.1 ft or 0.6%). Differences between the results for time steps of 100 days and 200 days are very small. Mass balance error has not been calculated as all fluxes are zero.

Command File DFTC06A.CFI (Note that the only difference in DFTC06B.CFI is DT=100 of DT=200).

```
OUTPUT DFTC06A.OUT
!
TITLE
VERIFICATION CASE NO. 6A -- CONSOLIDATION; RUN BY PVDH, BOULDER, CO.
TRANSIENT CONFINED 1D VERTICAL FLOW WITH PRESSURE-DEPENDENT PERMEABILITY.
REF.:  LAMBE AND WHITMAN, "SOIL MECHANICS," PAGES 406-410.
TEXT

  TERZAGHI'S FAMOUS SOLUTION.

  LET:

  k  = HYDRAULIC CONDUCTIVITY
     =   1.0
  Ss = SPECIFIC STORATIVITY
     =   1.0
  Sy = SPECIFIC YIELD
     =   1.0
  H0 = INITIAL HEAD
     = 200.0
  Hd = HEAD DROP
     =  50.0

  SOLUTION:

  SEE LAMBE AND WHITMAN, WHERE THE 1D CONSOLIDATION CURVES ARE
  PRESENTED IN A GRAPH.  THE APPX. SOLUTION FOR TWO POINTS,
  ONE AT THE MIDDLE OF THE LEAKY LAYER AND THE OTHER AT THE ONE-
  QUARTER ( OR THREE-QUARTER ) POINT IS AS FOLLOWS:

    TIME      MID-POINT      1/4 - POINT
   ------     ---------      -----------
    1000.       197.2           187.0
    2000.       188.5           177.5
    3000.       180.0           170.3
    4000.       173.7           166.7
    5000.       168.5           162.8
    6000.       164.3           160.0
    7000.       161.2           157.7
    8000.       158.8           155.8
    9000.       156.8           154.6
ENDT
GRID READ DFTC06.GRF FORM
LEVEL  9.
FREE
PROP
1,1.,1.,1.0,1.0,1.0,0.,0.,0.
ELEM  301.
ELEV   0.      LEVEL        1     NODE ALL
ELEV  12.5     LEVEL        2     NODE ALL
ELEV  25.      LEVEL        3     NODE ALL
ELEV  37.5     LEVEL        4     NODE ALL
ELEV  50.      LEVEL        5     NODE ALL
ELEV  62.5     LEVEL        6     NODE ALL
ELEV  75.      LEVEL        7     NODE ALL
ELEV  87.5     LEVEL        8     NODE ALL
ELEV  100.     LEVEL        9     NODE ALL
INIT 200.
INIT 150.      LEVELSING    1
```

```
FIX            LEVELSING     1
DT      200.
TOL     0.001
NOPR
ALPHA  1.8
ITER   30.
ITIN   50.
C00000000111111111122222222223333333333444444444455555555556666666666777777777778
C23456789012345678901234567890123456789012345678901234567890123456789012345678901234567890
HEAD           LEVELSING     5     NODE SING     1     SAVE DFTC6.T5  NOHD
HEAD           LEVELSING     9     NODE SING     1     SAVE DFTC6.T9  NOHD
GOTIL  1000.
HEAD           LEVELSING     5     NODE SING     1     SAVE DFTC6.T5  NOHD
HEAD           LEVELSING     9     NODE SING     1     SAVE DFTC6.T9  NOHD
PRIN
GOTIL 2000.
HEAD           LEVELSING     5     NODE SING     1     SAVE DFTC6.T5  NOHD
HEAD           LEVELSING     9     NODE SING     1     SAVE DFTC6.T9  NOHD
PRIN
GOTIL 3000.
HEAD           LEVELSING     5     NODE SING     1     SAVE DFTC6.T5  NOHD
HEAD           LEVELSING     9     NODE SING     1     SAVE DFTC6.T9  NOHD
PRIN
GOTIL 4000.
HEAD           LEVELSING     5     NODE SING     1     SAVE DFTC6.T5  NOHD
HEAD           LEVELSING     9     NODE SING     1     SAVE DFTC6.T9  NOHD
PRIN
GOTIL 5000.
HEAD           LEVELSING     5     NODE SING     1     SAVE DFTC6.T5  NOHD
HEAD           LEVELSING     9     NODE SING     1     SAVE DFTC6.T9  NOHD
PRIN
GOTIL 6000.
HEAD           LEVELSING     5     NODE SING     1     SAVE DFTC6.T5  NOHD
HEAD           LEVELSING     9     NODE SING     1     SAVE DFTC6.T9  NOHD
PRIN
GOTIL 7000.
HEAD           LEVELSING     5     NODE SING     1     SAVE DFTC6.T5  NOHD
HEAD           LEVELSING     9     NODE SING     1     SAVE DFTC6.T9  NOHD
PRIN
GOTIL 8000.
HEAD           LEVELSING     5     NODE SING     1     SAVE DFTC6.T5  NOHD
HEAD           LEVELSING     9     NODE SING     1     SAVE DFTC6.T9  NOHD
PRIN
GOTIL 9000.
HEAD           LEVELSING     5     NODE SING     1     SAVE DFTC6.T5  NOHD
HEAD           LEVELSING     9     NODE SING     1     SAVE DFTC6.T9  NOHD
PRIN
GOTIL 10000.
HEAD           LEVELSING     5     NODE SING     1     SAVE DFTC6.T5  NOHD
HEAD           LEVELSING     9     NODE SING     1     SAVE DFTC6.T9  NOHD
PRIN
XCFI
```

Grid File DFTC06.GRF

```
         4         2

         1       0.0       0.0
         2       1.0       0.0
         3       1.0       1.0
         4       0.0       1.0

         1         1         2         3
         2         1         3         4
```

Test 7: SEEPAGE FACE

tests #:	DFTC07
command files:	DFTC07.CFI
grid files:	DFTC07.GRF
output files:	DFTC07.OUT
date of test execution:	October 1996
title:	SEEPAGE: Horizontal one-dimensional unconfined flow with seepage face
description:	Steady-state horizontal one-dimensional flow between a reservoir and a seepage boundary in an isotropic, homogeneous, unconfined aquifer in the presence of a seepage face (see figure B7-1).

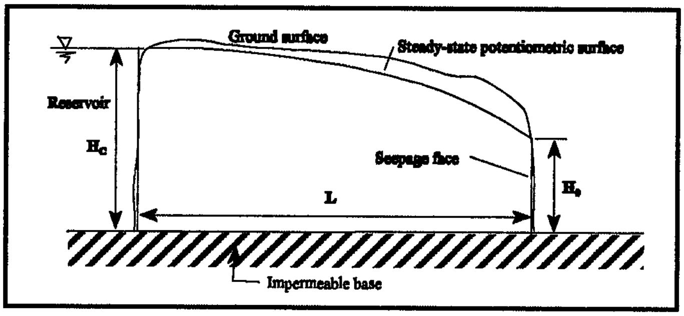


Figure B7-1.

tested functions:	Steady-state horizontal unconfined flow; node point head and flux computation; rising water algorithm; fixed head boundary condition; seepage face.
model domain:	Strip between two parallel drains with length and width of L = 100 ft, w = 10 ft, respectively.
boundary conditions:	Fixed head at left boundary h_c = 100 ft; although height of tail-water equals zero, fixed head at right boundary (L=100 ft) is set at 0.01 ft (at bottom layer only); other right side boundary nodes have rising water condition.
benchmark:	Analytical solution by Polibarinova-Kochina (1962) for height of seepage face and discharge at seepage face.
grid:	Three-dimensional grid with nine levels and eight layers; in plan view, the grid consists of 33 nodes in three rows, defining 40 elements (see figure B7-2).
initial conditions:	n.a. (steady state)
time-stepping:	n.a. (steady state)

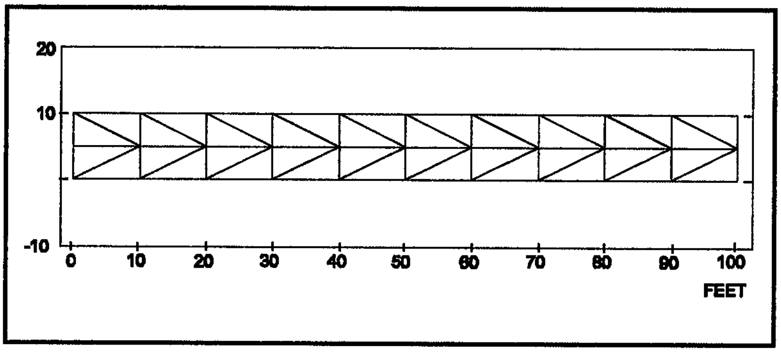


Figure B7-2.

system parameters: Hydraulic conductivity $K_x = K_y = K_z = 1.0$ ft/d.

control parameters: Tolerance = .1 ft; alpha = 1.5 (relaxation factor); acc not defined; max. # outer iterations = 30; max. # inner iterations = 50.

solver: ICCG

test performed by: Problem set up for numerical code prepared by code developers; code run and benchmark comparison performed by test report author.

type of comparison: Tabular listing of heads (see Table B7-1).

Table B7-1

	Seepage Face Height (ft)	Discharge (cu. ft/day)
Benchmark	37.5	500.0
DYNFLOW	37.65 (node 1) 37.50 (node 2) 36.31 (node 3) 37.15 (average)	inflow: 500.037 outflow: 500.046 mass balance error: 0.002%

performance note: Convergence reached in 13 outer iterations.

Command File DFTC07.CFI

```
OUTPUT DFTC07.OUT
!
TITL
VERIFICATION CASE NO. 7 -- SEEPAGE FACE
SEEPAGE STEADY-STATE PHREATIC 1D FLOW WITH SEEPAGE FACE.
REF.:  POLUBARINOVA-KOCHINA.
TEXT

  WHERE:

   H  = HEAD IN RESERVOIR.
   h0 = SEEPAGE FACE LENGTH.
   h  = TAILWATER ELEVATION.
   Q  = FLOW THROUGH DAM.
   k  = HYDRAULIC CONDUCTIVITY.
   l  = DISTANCE FROM RESERVOIR TO TAILWATER, THROUGH DAM.

  LET:

   H  = 100.0
   h  =   0.0
   l  = 100.0
   k  =   1.0

  SOLUTION:

     SEE FIGURES 220 - 225 IN REFERENCE, ON PAGES 292 - 294.
     THEY GIVE THE FOLLOWING SOLUTION --

     Ho = 37.5
     Q  = 500.0

ENDT
GRID READ DFTC07.GRF FORM
!
LEVEL  9.
FREE
PROP
1,1.,1.,1.,0.,0.,0.0,0.,0.
ELEM 301.
ELEV   0.      LEVELSING     1
ELEV  12.5     LEVELSING     2
ELEV  25.0     LEVELSING     3
ELEV  37.5     LEVELSING     4
ELEV  50.0     LEVELSING     5
ELEV  62.5     LEVELSING     6
ELEV  75.0     LEVELSING     7
ELEV  87.5     LEVELSING     8
ELEV 110.0     LEVELSING     9
INIT 100.00
INIT    0.01   LEVELSING     1     NODE RANGE    1    3
RISI           LEVELALL            NODE RANGE    1    3
FIX            LEVELALL            NODE RANGE   31   33
FIX            LEVELSING     1     NODE RANGE    1    3
DT    0.
TOL   0.1
PRAL
ALPHA 1.5
ITIN  50.
ITER  30.
GOTIL 0.
C00000000111111111122222222223333333333444444444455555555556666666666777777777778
C2345678901234567890123456789012345678901234567890123456789012345678901234567890
HEAD           LEVELSING     9     NODE RANGE    1    3SAVE DFTC09.CHK NOHD
XCFI
```

Grid File DFTC07.GRF

```
  33        40

   1         0      10.0
   2         0       5.0
   3         0         0
   4      10.0      10.0
   5      10.0       5.0
   6      10.0         0
   7      20.0      10.0
   8      20.0       5.0
   9      20.0         0
  10      30.0      10.0
  11      30.0       5.0
  12      30.0         0
  13      40.0      10.0
  14      40.0       5.0
  15      40.0         0
  16      50.0      10.0
  17      50.0       5.0
  18      50.0         0
  19      60.0      10.0
  20      60.0       5.0
  21      60.0         0
  22      70.0      10.0
  23      70.0       5.0
  24      70.0         0
  25      80.0      10.0
  26      80.0       5.0
  27      80.0         0
  28      90.0      10.0
  29      90.0       5.0
  30      90.0         0
  31     100.0      10.0
  32     100.0       5.0
  33     100.0         0

   1         5         4         1
   2         2         5         1
   3         3         5         2
   4         3         6         5
   5         8         7         4
   6         5         8         4
   7         6         8         5
   8         6         9         8
   9        11        10         7
  10         8        11         7
  11         9        11         8
  12         9        12        11
  13        14        13        10
  14        11        14        10
  15        12        14        11
  16        12        15        14
  17        17        16        13
  18        14        17        13
  19        15        17        14
  20        15        18        17
  21        20        19        16
  22        17        20        16
  23        18        20        17
  24        18        21        20
  25        23        22        19
  26        20        23        19
  27        21        23        20
  28        21        24        23
  29        26        25        22
  30        23        26        22
  31        24        26        23
  32        24        27        26
  33        29        28        25
  34        26        29        25
  35        27        29        26
  36        27        30        29
  37        32        31        28
  38        29        32        28
  39        30        32        29
  40        30        33        32
```

Test 8: MOUND

test #: DFTC08

input file: DFTC08.CFI

grid file: DFTC08.GRF

output file: DFTC08.OUT

date of test execution: November 1996

title: MOUND: horizontal one-dimensional unconfined (non-linear) flow (Dupuit) due to uniform recharge.

description: Steady-state horizontal flow between two fully penetrating canals with identical surface potentials in an isotropic, homogeneous, unconfined aquifer with a horizontal impermeable base subject to uniform recharge on top (see figure B8-1).

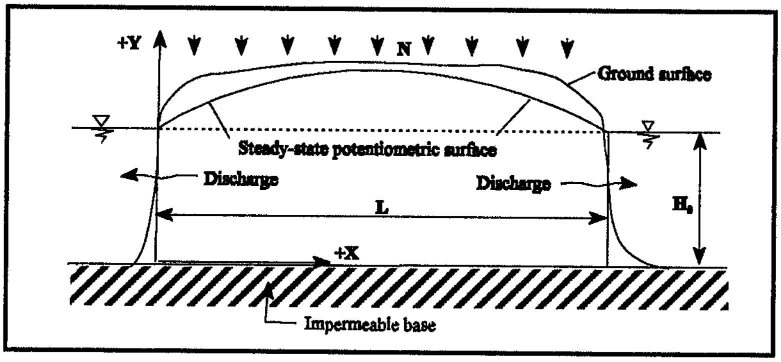


Fig. B8-1.

tested functions: Steady-state horizontal unconfined flow; node point head and flux computations; fixed head boundary condition; areal recharge.

model domain: Strip between two parallel drains with a length, width and thickness of L=100 ft, and w=10 ft, respectively.

boundary conditions: Constant head at left and right boundary h_0=50 ft; no-flow boundaries in y-direction, and at bottom; uniform recharge (flux) at top boundary.

benchmark: Analytical solution for a nonlinear potentiometric surface between two identical fixed head boundaries in a unconfined aquifer under steady-state conditions and uniform recharge:

$$h = \sqrt{h_0^2 + \frac{N}{k}(L-x)x}$$

and the discharge is calculated from:

$$Q = \frac{N}{2} L W$$

where N = recharge rate [L/T], Q = flow rate [L^3/T], k = horizontal hydraulic conductivity [L/T], H_0 = fixed head at boundaries [L], L = length of aquifer [L], and W = width of aquifer [L].

grid: Grid with five layer and six levels (0, 20, 40, 60, 80, and 200 ft); in plan view, the grid consists of 33 nodes in three rows, defining 40 elements (see figure B8-2); the horizontal definition of the grid is identical to the one used in the LINEAR test problem; heads are fixed below the top level to simulate unconfined conditions.

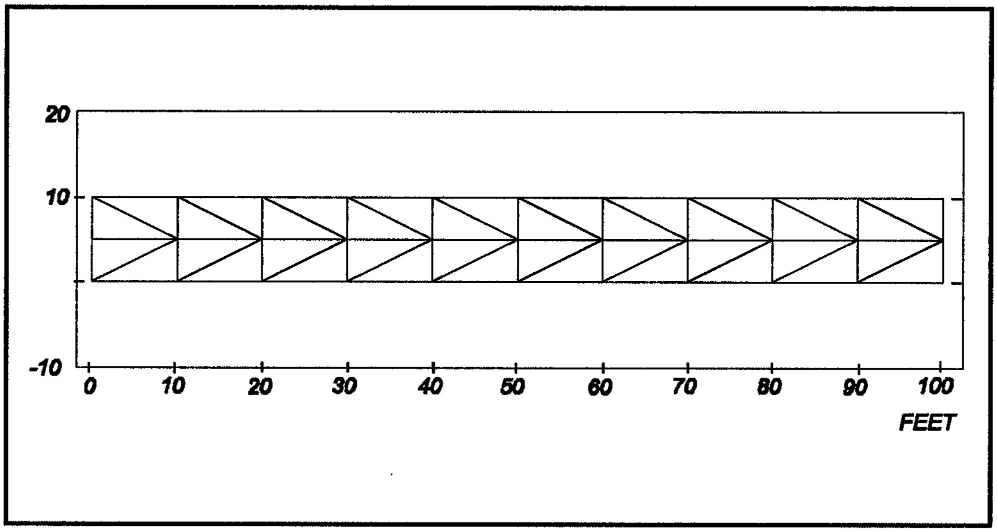


Figure B8-2.

initial conditions: n.a. (steady state)

time-stepping: n.a. (steady state)

system parameters: Hydraulic conductivity $K_x = K_y = 1.0$ ft/d; $K_z = 100.0$ ft/d; Recharge rate N = 1.25 ft/d.

control parameters: Tolerance = .001 ft; alpha = 1.5 (relaxation factor); acc not used; max. # outer iterations = 30; max. # inner iterations = 90

solver: ICCG

test performed by: Problem set up for numerical code prepared by code developers; code run and benchmark comparison performed by test report author.

type of comparison: Graphic plot of heads (see Fig. B8-3); tabular listing of heads (see Table B8-1); no statistical measures calculated.

Table B8-1

distance from downstream end (ft)	piezometric head (ft)						
	analytical solution	DYNFLOW DFTC08					
		level 1	level 2	level 3	level 4	level 5	level 6
0	50.	50. (FH)	50. (FH)	50. (FH)	50. (FH)	50. (FH)	50. (FH)
10	60.21	60.01	60.07	60.25	60.56	60.65	60.65
20	67.08	66.90	66.94	67.08	67.31	67.42	67.42
30	71.92	71.41	71.45	71.57	71.76	71.91	71.91
40	74.16	73.99	74.03	74.13	74.31	74.47	74.47
50	75.00	74.83	74.87	74.97	75.14	75.31	75.31
60	74.16	73.99	74.03	74.14	74.31	74.48	74.48
70	71.92	71.42	71.46	71.57	71.77	71.92	71.92
80	67.08	66.90	66.95	67.08	67.32	67.43	67.43
90	60.21	60.01	60.07	60.26	60.60	60.70	60.69
100	50.	50. (FH)	50. (FH)	50. (FH)	50. (FH)	50. (FH)	50. (FH)
maximum difference with benchmark per level [ft]		.51	.47	.35	.39	.49	.48
FH - Fixed Head Node (The numbers listed for each level are the average of three nodal values)							

Table B8-2

max # of outer iterations	6
influx	1250.149 ft^3/d
outflux	1250.149 ft^3/d
total mass balance error	.0%
max. head difference	.7%

performance notes: Resulting heads differ locally from the benchmark presented by the DYNFLOW authors (up to 0.7%; see Fig. B8-3). Computed flow rates for inflow and outflow (1250.149 ft^3/d) differ about 0.012% from the analytical results (2*625.0 ft^3/d).

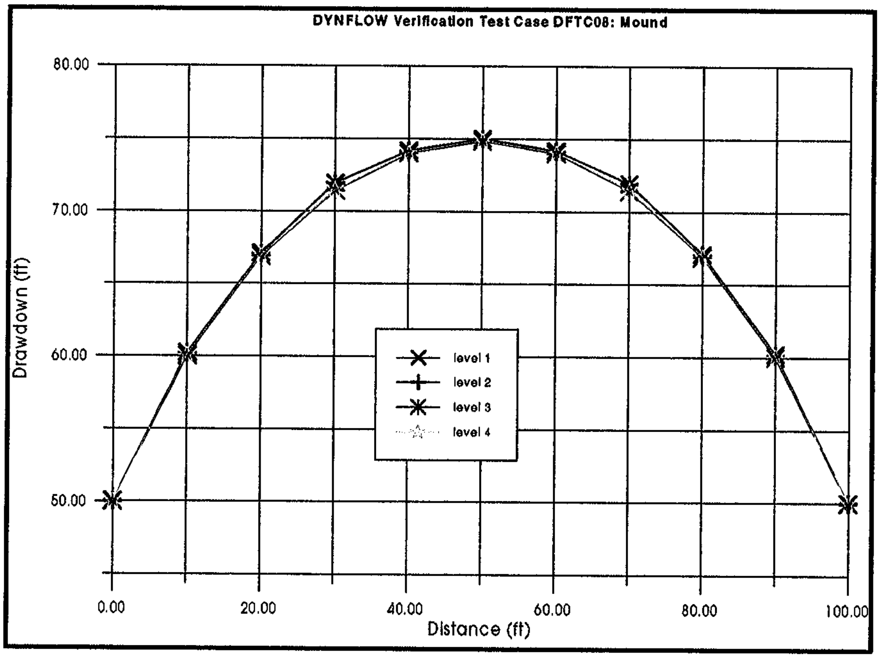


Figure B8-3.

Command File DFTC08.CFI

```
OUTPUT DFTC08.OUT
!
TITL
VERIFICATION CASE NO. 8 -- MOUND; RUN BY PVDH, BOULDER, CO.
DUPUIT STEADY-STATE UNCONFINED 1D HORIZ FLOW WITH UNIFORM RECHARGE
REF.:  WILSON IN BSCES/ASCE "GROUNDWATER HYDROLOGY," 1981.
TEXT

  H^2 = H0^2 + ( N / k )  ( L - x )  x

  Q   = ( N / 2 )  L  W
```

```
   WHERE:

     H  = HEAD AT ANY POINT x.
     x  = DISTANCE FROM ONE END OF THE AQUIFER TO THE OTHER.
     0  = POINT MARKER FOR "LEFT" OR "RIGHT" END OF AQUIFER.
     H0 = HEAD AT POINT 0.
     N  = RECHARGE.
     k  = HYDRAULIC CONDUCTIVITY.
     L  = LENGTH OF AQUIFER.
     ^2 = SQUARE.
     W  = WIDTH.

   LET:

     H0 =  50.0
     N  =   1.25
     L  = 100.0
     k  =   1.0
     W  =  10.0

   SOLUTION:

     H^2 = 2500 + 125  x - 1.25  x^2

      x     H
     ---   ---
     10.   60.21
     20.  67.08
     30.  71.59
     40.  74.16
     50.  75.00
     60.  74.16
     70.  71.59
     80.  67.08
     90.  60.21

     Q   =  625.0

ENDT
GRID READ DFTC08.GRF FORM
!
LEVEL  6.
FREE
PROP
1,1.,1.,100.,0.,0.,1.25,0.,0.
PROP
2,1.,1.,100.,0.,0.,1.25,0.,0.
ELEM 301.      LAYERRANGE   1    3
ELEM 302.      LAYERRANGE   4    6
ELEV   0.      LEVELSING    1
ELEV  20.      LEVELSING    2
ELEV  40.      LEVELSING    3
ELEV  60.      LEVELSING    4
ELEV  80.      LEVELSING    5
ELEV 200.      LEVELSING    6
INIT 50.
FIX            LEVELALL          NODE RANGE    1    3
FIX            LEVELALL          NODE RANGE   31   33
DT    0.
TOL   .001
PRAL
!DEBUG 1.
ALPHA 1.5
ITIN  90.
ITER   30.
GOTIL 0.
```

```
C00000000111111111122222222223333333333444444444455555555556666666666777777777778
C23456789012345678901234567890123456789012345678901234567890123456789012345678901234567890
HEAD          LEVELSING     1     NODE LIST            SAVE DFTC10.CHK
 2, 5, 8, 11, 14, 17, 20, 23, 26, 29, 32,
END
XCFI
```

Grid File DFTC08.GRF

```
        25         30

         1  -100.   0.                                          14 -1478.207  612.2935
         2   -92.388   38.2683                                  15    -1600.        0.
         3   -92.388  -38.2683                                  16 -1478.207 -612.2935
         4     -200.        0.                                  17 -2771.639 1148.0503
         5 -323.3578  133.9392                                  18    -3000.        0.
         6     -350.        0.                                  19 -2771.639 -1148.050
         7 -323.3578 -133.9392                                  20 -5543.227 2296.1006
         8 -600.5217  248.7442                                  21    -6000.        0.
         9     -650.        0.                                  22 -5543.227 -2296.101
        10 -600.5217 -248.7442                                  23 -11086.55 4592.2012
        11   -923.88   382.683                                  24  -12000.        0.
        12    -1000.        0.                                  25 -11086.55 -4592.201
        13   -923.88  -382.683

         1          1          2          4                     16         12         16         13
         2          1          4          3                     17         14         15         12
         3          2          5          4                     18         12         15         16
         4          3          4          7                     19         14         17         15
         5          5          6          4                     20         15         19         16
         6          4          6          7                     21         17         18         15
         7          5          8          6                     22         15         18         19
         8          6         10          7                     23         17         20         18
         9          8          9          6                     24         18         22         19
        10          6          9         10                     25         20         21         18
        11          8         11          9                     26         18         21         22
        12          9         13         10                     27         20         23         21
        13         11         12          9                     28         21         25         22
        14          9         12         13                     29         23         24         21
        15         11         14         12                     30         21         24         25
```

Test 9: CONFINED-UNCONFINED STORAGE CONVERSION

test #: DFTC09

command file: DFTC09N.CFI

grid file: DFTC09N.GRF

output file: DFTC09N.OUT

date of test execution: January 5, 1998

title: Confined-unconfined storage conversion

description: Transient radial-symmetric flow towards a fully penetrating pumping well with a constant discharge rate in an isotropic, homogeneous, porous medium of infinite extent and constant thickness; some time after pumping starts, the piezometric level in the initially fully confined aquifer decreases below the top of the aquifer and, locally, conditions become unconfined (see figure B9-1).

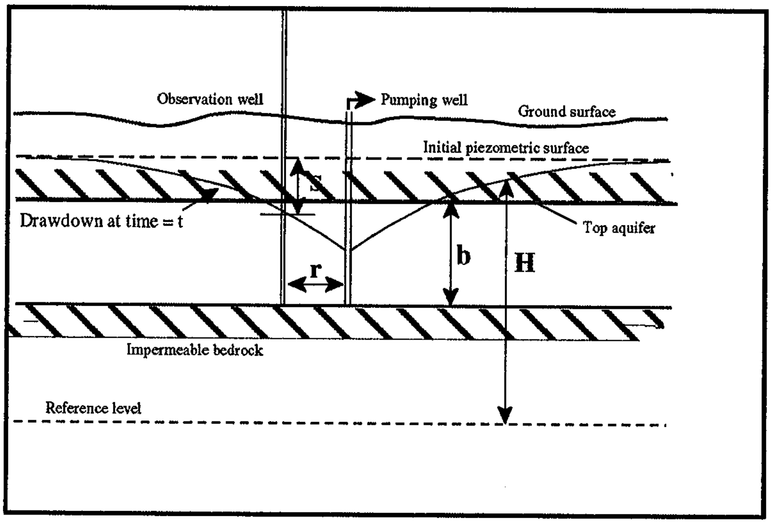


Figure B9-1.

tested functions: Transient horizontal flow under variably confined conditions; discharging well; unconfined/confined storage factor conversion.

model domain: *Analytical solution*: infinite horizontal domain and thickness of 800 ft; *numerical solution*: 1/2-quadrant (45°) with radius of 24,000 ft. and thickness of 800 ft.

benchmark: Analytical solution by Moench and Prickett (1972) for drawdown in a single, nonleaky, homogeneous, isotropic aquifer of infinite extent with water level conversion from confined to phreatic conditions; the well fully penetrates the aquifer and is infinitesimal in diameter:

$$h_1 = b - \frac{Q}{4\pi T}[W(u_1) - W(v)]$$

and

$$h_2 = H - \frac{(H-b)\ W(u_2)}{W(v\alpha_1/\alpha_2)}$$

where

$$W(x) = \int_z^\infty \frac{e^{-z}}{z}\,dz \quad [dimensionless]$$

$$u_1 = \frac{r^2\ S_1}{4tT} \quad [dimensionless]$$

$$u_2 = \frac{r^2\ S_2}{4tT} \quad [dimensionless]$$

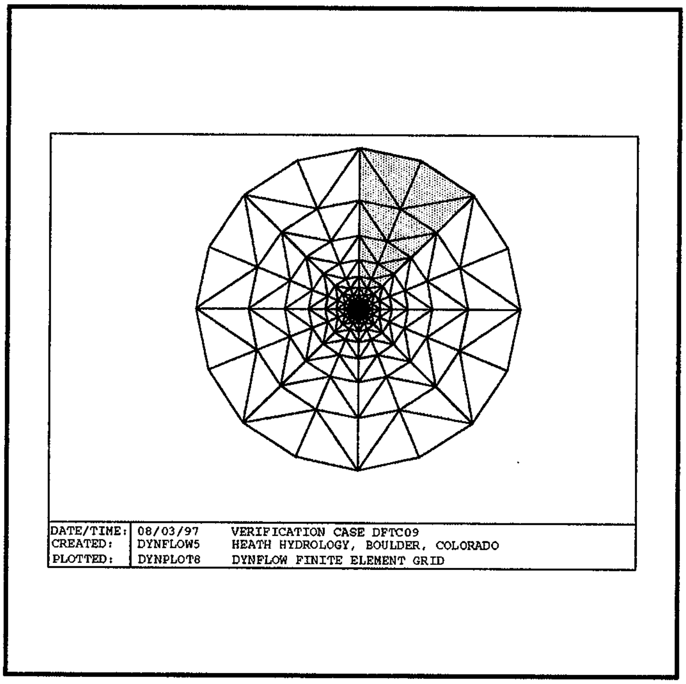
$$v = \frac{R^2\ S_1}{4tT} \quad [dimensionless]$$

and $\boldsymbol{Q}$ = pumping rate [L^3/T], $\boldsymbol{T}$ = aquifer transmissivity [L^2/T] = $k_h\ b$, k_h = horizontal hydraulic conductivity of aquifer [L/T], $\boldsymbol{b}$ = thickness of aquifer [L], S_1 = storativity under water table conditions [fraction], S_2 = storativity under confined conditions [fraction], α_1 = aquifer diffusivity (= T/S_1) [L^2/T], α_2 = aquifer diffusivity (= T/S_2) [L^2/T], $\boldsymbol{r}$ = distance from well [L], $\boldsymbol{R}$ = radial distance to point of conversion [L], $\boldsymbol{t}$ = time since start of pumping [T], h_1 = elevation of water table (unconfined conditions) from bottom aquifer [L], h_2 = elevation of piezometric surface (confined conditions) from bottom aquifer [L].

Calculations are made for observation wells at r = 100, 350, 650, and 1000 ft from the well.

grid: Single layer 1/2-quadrant (45°) grid of 24,000 ft radius and two levels (see Figure B9-2) with actual location of well as origin of radial-symmetrical grid; in plan view, the grid consists of 30 nodes defining 36 elements; levels are located at elevation 0.0 and 800.0 ft, respectively.

boundary conditions: Fixed head at outer radial boundary (R=24,000 ft) is h_R = 802 ft; total well discharge rate Q_{tot} = 33648 ft^3/d; Q_m = 1/8 of Q_{tot} is distributed as a specified flux boundary condition in the 3 nodes located about 100 ft from the center of the quadrant at both level 1 and 2, *i.e.*, 1/6 of Q_m per node or 1/48 of Q_{tot} (= 701 ft^3/d); remaining boundary nodes are specified as no-flow boundaries.



DATE/TIME:	08/03/97	VERIFICATION CASE DFTC09
CREATED:	DYNFLOW5	HEATH HYDROLOGY, BOULDER, COLORADO
PLOTTED:	DYNPLOT8	DYNFLOW FINITE ELEMENT GRID

Figure B9-2.

initial conditions: H = 802.0 ft, with H being 2.0 ft above top of top level.

time-stepping: Calculations made for 5 time steps : 0.1, 1.0, 10.0, 100.0, and 1000.0 days.

system parameters: Hydraulic conductivity $k_x = k_y = K_h = 3.34$ ft/d; $k_z = K_v = 33.4$ ft/d; specific storativity $S_s = 1.25*10^{-6}$ ft^{-1} (storage coefficient $S = S_s* b = 0.001$; dimensionless); storativity or specific yield for unconfined conditions = 0.10 (dimensionless).

control parameters: Tolerance = .001 ft; acce = 1.4; max. # outer iterations = 30.

solver: ICCG

test performed by: Problem set up for numerical code prepared by code developers; code run and benchmark comparison performed by test report author.

type of comparison: Graphic plot of heads (see Fig. B9-3); tabular listing of heads (see Table B9-1, and B9-2; no statistical measures calculated.

Table B9-1.

time (days)	drawdown (ft)							
	r =200 ft		r=350 ft		r=650 ft		r=1000 ft	
	M-P1)	DF2) average nodes 5,6,7	M-P1)	DF2) average nodes 8,9,10	M-P1)	DF2) average nodes 11,12,13	M-P1)	DF2) average nodes 14,15,16
t_1= 0.1	1.28	1.63	0.79	1.08	0.33	0.48	0.11	0.17
t_2= 1.0	2.42	2.55	1.82	1.92	1.26	1.34	0.88	0.93
t_3= 10.0	4.42	4.33	3.38	3.31	2.39	2.35	1.91	1.91
t_4= 100.0	6.70	6.50	5.59	5.42	4.37	4.26	3.56	3.48
t_5= 1000.0	9.00	8.82	7.88	7.74	6.64	5.54	5.79	5.71

1) M-P: Moench-Prickett solution (MathCAD)
2) DYNFLOW : for each time, the range of values (for different levels) is given

Table B9-2. Global fluxes in ft^3/d

time step	t_1	t_2	t_3	t_4	t_5
# iterations	2	2	2	2	3
influx including storage	4290.2	4369.8	4457.9	4512.8	4597.0
outflux	4290.2	4379.1	4456.1	4512.4	4593.4
total mass balance error	0.01%	0.21%	0.04%	0.01%	0.08%

performance notes: In comparing DYNFLOW with the benchmark, a trend can be observed: for short times the drawdown computed is greater than that of the benchmark, while for long times, the reverse is the case. The mass balance is generally good, except for time equals 1 day. The discrepancies between the code and the benchmark may result in part from inaccuracies in the execution of the benchmark. In programming the benchmark in Mathcad (MathSoft, Inc.), it was tested against the data given in the paper by Moench and Prickett (1972). The actual benchmark used in this test case uses modified data.

reference: Moench, A.F., and T.A. Prickett. (1972). Radial Flow in an Infinite Aquifer Undergoing Conversion from Artesian to Water Table Conditions. Water Resources Research, Vol. 8(2), pp. 494-499.

Command File DFTC09N.CFI

```
OUTPUT DFTC09N.OUT

! RHF Revisions:

!    Extended grid (24,000 foot radius) (DFTC09N.GRF)
!    1-layer, 2-level model
!    pumping evenly distributed between levels and among 3 nodes
!       at center of grid
!    Do not fix far boundary nodes

TITLE
VERIFICATION CASE NO. 9 -- MIXED CONFINED/UNCONFINED; RUN BY PVDH, BOULDER, CO.
TRANSIENT CONFINED AND UNCONFINED CONDITIONS (MIXED) EXTENDED GRID
REF.:  MOENCH AND PRICKETT (1972) WRR 8(2):494-499.
TEXT

  LET:

  Kh = HORIZ HYDRAULIC CONDUCTIVITY
     = 3.34
  Kv = VERT  HYDRAULIC CONDUCTIVITY
     = 10*kh
  b  = AQUIFER THICKNESS
     = 800.
  Ss = CONFINED STORATIVITY
     = 0.00000125
  Sy = UNCONFINED STORATIVITY
     = 0.10
  Q  = WELL PUMPING RATE
     = 33648.
  ALSO, LET THE INITIAL HEAD ( H ) = 802, SO THAT
       H - b = 2.0

ENDT

GRID DFTC09N.GRF FORM
LEVEL  2.
FREE NODE ALL
ELEV   0.     LEVELSING     1
ELEV  800.    LEVELSING     2
PROP
1,3.34,3.34,33.4,0.00000125,0.10,0.
MATNUM  301.  ELEM ALL LAYER ALL
INIT    802.  NODE ALL LAYER ALL
FLUX -701  LEVEL  1 2  NODE    2 3 4
ITER  30.
ACCE  1.4
TOL   0.001
PRAL
NOPR
HEAD           LEVEL    1  2    NODE    14 15 16     SAVE DFTC9.T0 NOHD
DT    .01
GOTIL .1
HEAD           LEVEL    1  2    NODE    14 15 16     SAVE DFTC9.TP1 NOHD
PRIN
DT    0.1
GOTIL 1.0
HEAD           LEVEL    1  2    NODE    14 15 16     SAVE DFTC9.T1 NOHD
PRIN
DT      1.0
GOTIL   10.0
HEAD           LEVEL    1  2    NODE    14 15 16     SAVE DFTC9.T10 NOHD
PRIN
DT      10.0
GOTIL  100.0
HEAD           LEVEL    1  2    NODE    14 15 16     SAVE DFTC9.T1C NOHD
```

```
PRIN
DT     100.0
GOTIL 1000.0
HEAD          LEVEL     1  2     NODE     14 15 16      SAVE DFTC9.T1K NOHD
PRIN
END
```

Grid File DFTC09N.GRF

```
         30         36

          2      100.0        .000                                  17       1600.        .000
          3      92.39       38.27                                  18       1478.       612.3
          4      70.71       70.71                                  19       1131.       1131.
          5      200.0        .000                                  20       3000.        .000
          6      184.8       76.54                                  21       2772.       1148.
          7      141.4       141.4                                  22       2121.       2121.
          8      350.0        .000                                  23       6000.        .000
          9      323.4       133.9                                  24       5543.       2296.
         10      247.5       247.5                                  25       4243.       4243.
         11      650.0        .000                                  26      12000.        .000
         12      600.5       248.7                                  27      11087.       4592.
         13      459.6       459.6                                  28       8485.       8485.
         14      1000.        .000                                  29      24000.        .000
         15      923.9       382.7                                  30      22173.       9184.
         16      707.1       707.1                                  31      16971.      16971.

          3          2          5          3                        21          15          19          16
          4          5          6          3                        22          15          18          19
          5          3          7          4                        23          17          20          18
          6          3          6          7                        24          20          21          18
          7          5          8          6                        25          18          22          19
          8          8          9          6                        26          18          21          22
          9          6         10          7                        27          20          23          21
         10          6          9         10                        28          23          24          21
         11          8         11          9                        29          21          25          22
         12         11         12          9                        30          21          24          25
         13          9         13         10                        31          23          26          24
         14          9         12         13                        32          26          27          24
         15         11         14         12                        33          24          28          25
         16         14         15         12                        34          24          27          28
         17         12         16         13                        35          26          29          27
         18         12         15         16                        36          29          30          27
         19         14         17         15                        37          27          31          28
         20         17         18         15                        38          27          30          31
```

Test 10: RISING/FALLING WATER TABLE (WETTING FRONT)

PART A: RISING WATER TABLE (RESATURATION)

tests #: DFTC10A

command files: DFTC10AN.CFI

grid file: DFTC10N.GRF

output files: DFTC10AN.OUT

date of test execution: January 6, 1998

title: Rising water-table (wetting front or resaturation)

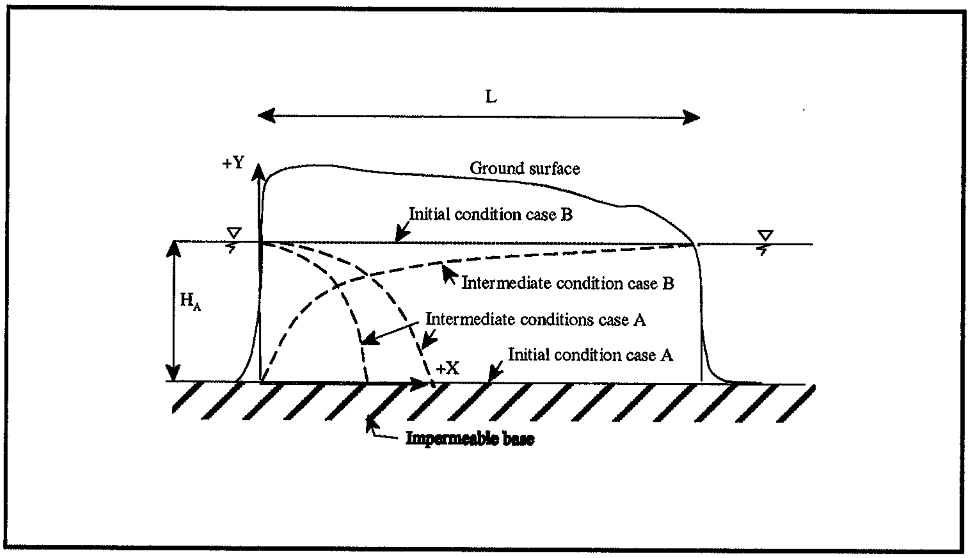


Figure B10-1.

description: Transient flow in a multi-layer, rectangular isotropic, homogeneous, unconfined aquifer; flow starts after sudden rise of fixed head boundary condition at $T = 0$ at one side of the semi-infinite model domain (from $H = 0$ to $H = H_A$).

In the numerical model, the fixed head at the opposite side remains constant during the simulation ($H = 0$) assuming that this boundary is far enough away from other the opposite boundary to have a negligible influence on the distribution of heads within the aquifer for the time period selected; no-flow conditions exist on the other two parallel sides (see figure B10-1).

tested functions:	Unconfined potentiometric surface calculation (correctness/accuracy); (re-)wetting of dry elements by rising water table (correctness/stability).
model domain:	Strip between two parallel drains with a length L=100 ft and a width W=10 ft.
boundary conditions:	Constant head at left boundary (x = 0 ft) is $h_0 = 10$ ft; constant head at right boundary (x = 100 ft) is $h_L = 0$ ft; no-flow boundaries in y- and z-direction.
benchmark:	Transient solution as given by Polubarinova-Kochina (1962) and programmed in Mathcad (MathSoft, Inc.) using the following dimensionless variables: $= [(x^2 * S_y) / (2 * K * H_0 * t)]^{\frac{1}{2}}; \quad = \quad / \sqrt{2}; u = H(x,t)/H_0$ where S_y = specific yield, K = horizontal hydraulic conductivity, H_0 = boundary condition at surface water boundary, x = distance from surface water boundary, and t = time since change occurred in boundary condition. The Mathcad implementation has been based on the equations presented in pp. 508-510 of Polubarinova-Kochina (1962); the values used for comparison are those listed in Table 17 and Fig. 378 on p. 509 (Mathcad worksheet PK-508.mcd). For comparison with the numerical model, a new data set has been created Mathcad worksheet PK-508a.mcd to keep the progressing toe within a small section of the model domain away from the constant head boundary. Note: The values for the parameters and time stepping are chosen such that the effect of the sudden change in head at one boundary has not reached the opposite boundary by the end of the simulation.
grid:	Two-dimensional horizontal grid with six levels and five layers; each layer is 2 ft thick, except for the top layer which is set at 3 ft; in plan view, the grid consists of 63 nodes in three rows, defining 80 elements per layer (see figure B10-2).
initial conditions:	h = 0 ft.
time-stepping:	At the start DT= 0.02 days until time = 1.0 days, then DT=0.05 until time = 5 days; finally, DT =0.1 until time = 10 days (the small initial time steps are chosen to keep the mass balance error small and allow the program to converge within the iteration bounds).
system parameters:	Hydraulic conductivity $K_x = K_y = 1.0$ ft/d; $K_z = 100$ ft/d; specific yield $S_y = 0.1$.
control parameters:	Tolerance = .001 ft; alpha = 1.5 (relaxation factor); max. # outer iterations = 30; max. # inner iterations = 50.
solver:	ICCG
test performed by:	Problem set up for numerical code, code run and benchmark comparison performed by test report author.

type of comparison: Tabular listing of heads (see Table B10-1 and B10-2); iteration progress, steady-state discharge calculation; no statistical measures calculated.

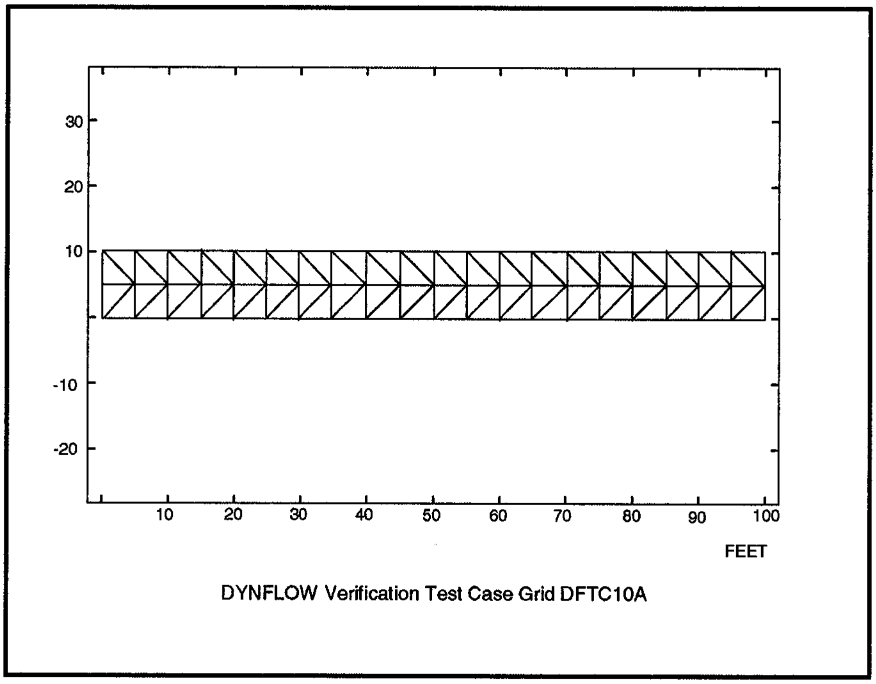


Figure B10-2.

Table B10-1: Results Case A - Head comparison for rising water table at various times

	Time = 2 days			Time = 5 days			Time = 10 days		
X	***PK*** [1)]	***DF*** [2)]	**Δ*H*** [3)]	***PK*** [1)]	***DF*** [2)]	**Δ*H*** [3)]	***PK*** [1)]	***DF*** [2)]	**Δ*H*** [3)]
10	6.35	6.38 [6.38]	0.03	7.81	7.82 [7.82]	0.01	8.50	8.50 [8.50]	0.
20	1.58	1.48 [1.66]	-0.10	5.20	5.21 [5.21]	0.01	6.78	6.79 [6.79]	0.01
30	<0	0.	0.	2.13	2.13 [2.15]	0.	4.85	4.86 [4.86]	0.01
40	<0	0.	0.	<0	.01 [.02]	0.01	2.69	2.69 [2.69]	0.
50	<0	0.	0.	<0	0.	0.	0.28	0.32 [0.41]	0.04
60	<0	0.	0.	<0	0.	0.	<0	0.	0.
70	<0	0.	0.	<0	0.	0.	<0	0.	0.
80	<0	0.	0.	<0	0.	0.	<0	0.	0.
90	<0	0.	0.	<0	0.	0.	<0	0.	0.

1) Analytical solution according to Polibarinova-Kochina

2) DYNFLOW results are given as the average head in all relevant nodes (i.e., having the same distance from origin) for all levels followed in brackets by the average head in the nodes on the center grid line for all levels.

3) Difference between numerical model and benchmark; positive number indicates overprediction by numerical model.

Table B10-2: Code Performance.

test case DFTC10A			
time	2 days	5 days	10 days
# of iterations	3	2	2
influx [ft^3/d]	40.593	19.723	14.054
outflux [ft^3/d]	-40.588	-19.719	-14.039
total mass balance error	0.01%	0.02%	0.10%

performance notes:	To obtain an accurate mass balance, initial time steps had to be reduced to very small values and the grid refined (original grid for this case was identical to that for case 10B). The head comparison is excellent, including in the area near the infiltration front.
reference:	Polubarinova-Kochina, P.Ya. 1962. Theory of Groundwater Movement. Princeton University Press, Princeton, New Jersey, 613p.

Command File DFTC10AN.CFI for test DFTC10A

```
OUTPUT DFTC10AN.OUT

! RHF Revisions:
!     New grid with 5-foot node spacing in x-direction
!     Lumped storage option selected, i.e. storage flux not distributed
!       to adjacent nodes

TITLE
VERIFICATION CASE NO. 10A -- RISING WATER TABLE (WETTING FRONT/REWETTING)
TRANSIENT UNCONFINED FLOW WITH SUDDEN CHANGE IN FIXED HEAD BOUNDARY CONDITION
RUN BY PVDH, BOULDER, CO. -- INCREASED GRID RESOLUTION

GRID READ DFTC10N.GRF FORM
LEVEL  6.
FREE
PROP
1,1.,1.,100.,0.,0.1,0.
ELEM  301.
ELEV   0.      LEVELSING     1
ELEV   2.      LEVELSING     2
ELEV   4.      LEVELSING     3
ELEV   6.      LEVELSING     4
ELEV   8.      LEVELSING     5
ELEV  11.      LEVELSING     6
INIT 0.0       NODE ALL LEVEL ALL
INIT  10.      LEVELALL           NODE RANGE    1    3
FIX            LEVELALL           NODE RANGE    1    3
TOL   .001
ITER  30.
ITIN  50.
PRAL
NOPR
DT    0.02

! LUMPED STORAGE OPTION
STORE 1

GOTIL 1.0
DT    0.05
GOTIL 2.0
HEAD           LEVELSING     6    NODE ALL          SAVE NEW10.T2 NOHD
PRIN
GOTIL 5.0
PRIN
HEAD           LEVELSING     6    NODE ALL          SAVE NEW10.T5 NOHD
DT=0.1
GOTIL 10.0
HEAD           LEVELSING     6    NODE ALL          SAVE NEW10.T10 NOHD
PRIN
END
```

Grid File DFTC10N.GRF

```
  63       80

   1     .000     .000
   2     .000    5.000
   3     .000    10.00
   4    5.000     .000
   5    5.000    5.000
   6    5.000    10.00
   7    10.00     .000
   8    10.00    5.000
   9    10.00    10.00
  10    15.00     .000
  11    15.00    5.000
  12    15.00    10.00
  13    20.00     .000
  14    20.00    5.000
  15    20.00    10.00
  16    25.00     .000
  17    25.00    5.000
  18    25.00    10.00
  19    30.00     .000
  20    30.00    5.000
  21    30.00    10.00
  22    35.00     .000
  23    35.00    5.000
  24    35.00    10.00
  25    40.00     .000
  26    40.00    5.000
  27    40.00    10.00
  28    45.00     .000
  29    45.00    5.000
  30    45.00    10.00
  31    50.00     .000
  32    50.00    5.000
  33    50.00    10.00
  34    55.00     .000
  35    55.00    5.000
  36    55.00    10.00
  37    60.00     .000
  38    60.00    5.000
  39    60.00    10.00
  40    65.00     .000
  41    65.00    5.000
  42    65.00    10.00
  43    70.00     .000
  44    70.00    5.000
  45    70.00    10.00
  46    75.00     .000
  47    75.00    5.000
  48    75.00    10.00
  49    80.00     .000
  50    80.00    5.000
  51    80.00    10.00
  52    85.00     .000
  53    85.00    5.000
  54    85.00    10.00
  55    90.00     .000
  56    90.00    5.000
  57    90.00    10.00
  58    95.00     .000
  59    95.00    5.000
  60    95.00    10.00
  61    100.0     .000
  62    100.0    5.000
  63    100.0    10.00
```

```
      1         1         5         2                     41        31        35        32
      2         2         5         3                     42        32        35        33
      3         1         4         5                     43        31        34        35
      4         3         5         6                     44        33        35        36
      5         4         8         5                     45        34        38        35
      6         5         8         6                     46        35        38        36
      7         4         7         8                     47        34        37        38
      8         6         8         9                     48        36        38        39
      9         7        11         8                     49        37        41        38
     10         8        11         9                     50        38        41        39
     11         7        10        11                     51        37        40        41
     12         9        11        12                     52        39        41        42
     13        10        14        11                     53        40        44        41
     14        11        14        12                     54        41        44        42
     15        10        13        14                     55        40        43        44
     16        12        14        15                     56        42        44        45
     17        13        17        14                     57        43        47        44
     18        14        17        15                     58        44        47        45
     19        13        16        17                     59        43        46        47
     20        15        17        18                     60        45        47        48
     21        16        20        17                     61        46        50        47
     22        17        20        18                     62        47        50        48
     23        16        19        20                     63        46        49        50
     24        18        20        21                     64        48        50        51
     25        19        23        20                     65        49        53        50
     26        20        23        21                     66        50        53        51
     27        19        22        23                     67        49        52        53
     28        21        23        24                     68        51        53        54
     29        22        26        23                     69        52        56        53
     30        23        26        24                     70        53        56        54
     31        22        25        26                     71        52        55        56
     32        24        26        27                     72        54        56        57
     33        25        29        26                     73        55        59        56
     34        26        29        27                     74        56        59        57
     35        25        28        29                     75        55        58        59
     36        27        29        30                     76        57        59        60
     37        28        32        29                     77        58        62        59
     38        29        32        30                     78        59        62        60
     39        28        31        32                     79        58        61        62
     40        30        32        33                     80        60        62        63
```

PART B: FALLING WATER TABLE (DESATURATION)

tests #: DFTC10B

command files: DFTC10B.CFI

grid files: DFTC10.GRF

output files: DFTC10B.OUT

date of test execution: October 8, 1997

title: Falling water-table (desaturation/dewatering)

description: Transient flow in a multi-layer, rectangular isotropic, homogeneous, unconfined aquifer; flow after sudden fall of fixed head (from $H = H_A$ to $H = 0$) at T=0 at one side of the semi-infinite model domain.

In the numerical model, the fixed head at the opposite side remains constant during the simulation ($H = H_A$) assuming that this boundary is far enough away from other the opposite boundary to have a negligible influence on the distribution of heads within the aquifer for the time period selected; no-flow conditions exist on the other two parallel sides (see figure B10-1).

tested functions: Unconfined potentiometric surface calculation (correctness/accuracy); drainage of wet elements (dewatering) by falling water table (correctness/stability).

model domain: Strip between two parallel drains with a length L=100 ft and a width W=10 ft.

boundary conditions: Constant head at left boundary (x = 0 ft) is $h_0 = 0$ ft; constant head at right boundary (x = 100 ft) is $h_L = 10$ ft; no-flow boundaries in y- and z-direction.

benchmark: Transient solution as given by Polubarinova-Kochina (1962) and programmed in Mathcad (MathSoft, Inc.) using the following dimensionless variables:

$= [(x^2 * S_y) / (2 * K * H_0 * t)]^{½}$; $=$ $/ \sqrt{2}$; $u = H(x,t)/H_0$

where S_y = specific yield, K = horizontal hydraulic conductivity, H_0 = boundary condition at surface water boundary, x = distance from surface water boundary, and t = time since change occurred in boundary condition.

The mathcad implementation has been based on the equations presented in pp. 506-507 of Polubarinova-Kochina (1962); the values used for comparison are those listed in Table 17 and Fig. 377 on p. 508 (MathCAD worksheet PK-506.mcd). For comparison with the numerical model, a new data set has been created Mathcad worksheet PK-506a.mcd to keep the progressing toe within a small section of the model domain away from the constant head boundary.

Note: The values for the parameters and time stepping are chosen such that the effect of the sudden change in head at one boundary has not reached the opposite boundary by the end of the simulation.

grid: Two-dimensional horizontal grid with six levels and five layers; each layer is 2 ft thick, except for the top layer which is set at 3 ft; in plan view, the grid consists of 33 nodes in three rows, defining 40 elements per layer (see figure B10-3).

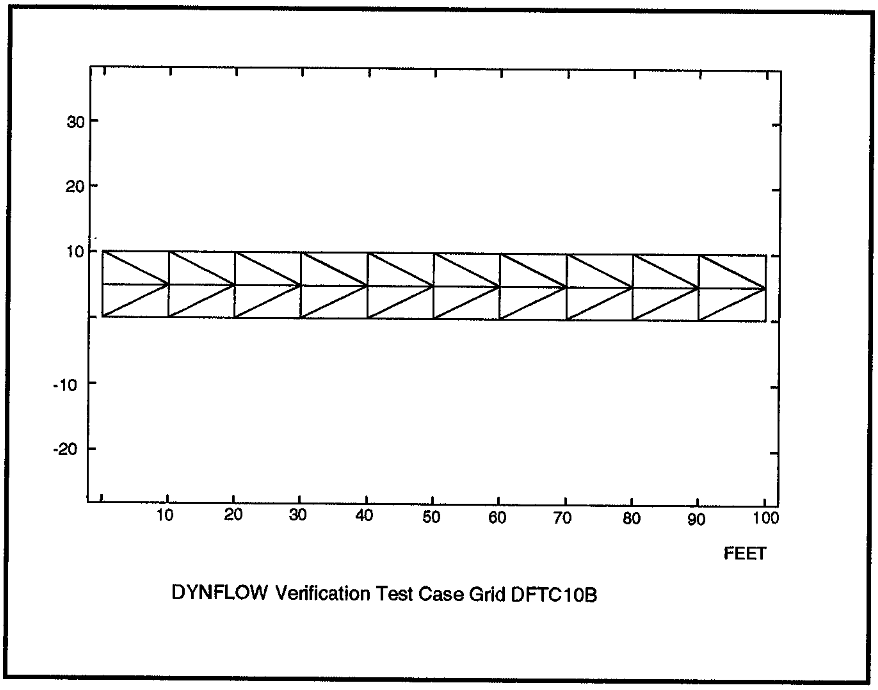


Figure B10-3.

initial conditions: h = 10 ft.

time-stepping: At the start DT= 0.02 days until time = 1.0 days, then DT=0.05 until time = 5 days; finally, DT =0.1 until time = 10 days (small initial time steps are chosen to keep the mass balance error small and allow the program to converge within the iteration bounds).

system parameters: Hydraulic conductivity $K_x = K_y = 1.0$ ft/d; $K_z = 100$ ft/d; specific yield $S_y = 0.1$.

control parameters: tolerance = .001 ft; alpha = 1.5 (relaxation factor); max. # outer iterations = 30; max. # inner iterations = 50.

solver: ICCG

test performed by: Problem set up for numerical code, code run and benchmark comparison performed by test report author.

type of comparison: Tabular listing of heads (see Table B10-3 and B10-4); iteration progress, steady-state discharge calculation; no statistical measures calculated.

Table B10-3: Results Case B - Head comparison for falling water table

	Time = 10 days		
X	***PK*** 1)	***DF*** 2)	**Δ*H*** 3)
10	4.52	4.45-4.53 [4.47]	-0.05
20	6.22	6.18-1.19 [6.18]	-0.04
30	7.37	7.33-7.34 [7.33]	-0.04
40	8.19	8.16 [8.16]	-0.03
50	8.78	8.75 [8.75]	-0.03
60	9.20	9.17 [9.17]	-0.03
70	9.49	9.46 [9.46]	-0.03
80	9.68	9.64 [9.64]	-0.04
90	9.80	9.75 [9.75]	-0.05
100	9.87	9.78 [9.78]	-0.09

1) Analytical solution according to Polibarinova-Kochina

2) DYNFLOW results are given as a range for all relevant nodes (i.e., same distance from origin) followed by the average value between brackets.

3) Difference between numerical model and benchmark; negative number indicates underprediction by numerical model.

performance notes: This problem is easier to solve for the code than the rising water table case; head deviations and mass balance errors are very small, especially for larger time.

reference: Polubarinova-Kochina, P.Ya. 1962. Theory of Groundwater Movement. Princeton University Press, Princeton, New Jersey, 613p.

Table B10-4: Code Performance.

test case	DFTC10B	
time	2 days	10 days
# of iterations outer/(inner)	6(2)	6(2)
influx [ft^3/d]	74.306	63.475
outflux [ft^3/d]	-74.307	-63.478
total mass balance error	0.001%	0.005%

Command File DFTC10B.CFI for test DFTC10B

```
OUTPUT DFTC10B.OUT

TITLE
VERIFICATION CASE NO. 10B -- FALLING WATER TABLE (DEWATERING)
TRANSIENT UNCONFINED FLOW WITH SUDDEN CHANGE IN FIXED HEAD BOUNDARY CONDITION
RUN BY PVDH, BOULDER, CO.
GRID READ DFTC10.GRF FORM
LEVEL  6.
FREE
PROP
1,1.,1.,100.,0.,0.1,0.
ELEM  301.
ELEV   0.      LEVELSING     1
ELEV   2.      LEVELSING     2
ELEV   4.      LEVELSING     3
ELEV   6.      LEVELSING     4
ELEV   8.      LEVELSING     5
ELEV  11.      LEVELSING     6
INIT  10.      NODE ALL LAYER ALL
INIT   0.      LEVELALL            NODE RANGE    1    3
FIX            LEVELALL            NODE RANGE    1    3
TOL   .001
ALPHA 1.5
ITER  30.
ITIN  50.
PRAL
NOPR
DT    0.02
GOTIL 1.0
DT    0.05
GOTIL 2.0
HEAD           LEVELSING     6     NODE ALL          SAVE DFTC10B.T6 NOHD
```

```
PRIN
GOTIL 5.0
PRIN
HEAD           LEVELSING     6     NODE ALL           SAVE DFTC10B.T6 NOHD
DT=0.1
GOTIL 10.0
HEAD           LEVELSING     6     NODE ALL           SAVE DFTC10B.T6 NOHD
PRIN
END
```

Grid File DFTC10.GRF for test case DFTC10B

```
      33        40         5

       1         0      10.0                                    18      50.0         0
       2         0       5.0                                    19      60.0      10.0
       3         0         0                                    20      60.0       5.0
       4      10.0      10.0                                    21      60.0         0
       5      10.0       5.0                                    22      70.0      10.0
       6      10.0         0                                    23      70.0       5.0
       7      20.0      10.0                                    24      70.0         0
       8      20.0       5.0                                    25      80.0      10.0
       9      20.0         0                                    26      80.0       5.0
      10      30.0      10.0                                    27      80.0         0
      11      30.0       5.0                                    28      90.0      10.0
      12      30.0         0                                    29      90.0       5.0
      13      40.0      10.0                                    30      90.0         0
      14      40.0       5.0                                    31     100.0      10.0
      15      40.0         0                                    32     100.0       5.0
      16      50.0      10.0                                    33     100.0         0
      17      50.0       5.0

       1         5         4         1                          21        20        19        16
       2         2         5         1                          22        17        20        16
       3         3         5         2                          23        18        20        17
       4         3         6         5                          24        18        21        20
       5         8         7         4                          25        23        22        19
       6         5         8         4                          26        20        23        19
       7         6         8         5                          27        21        23        20
       8         6         9         8                          28        21        24        23
       9        11        10         7                          29        26        25        22
      10         8        11         7                          30        23        26        22
      11         9        11         8                          31        24        26        23
      12         9        12        11                          32        24        27        26
      13        14        13        10                          33        29        28        25
      14        11        14        10                          34        26        29        25
      15        12        14        11                          35        27        29        26
      16        12        15        14                          36        27        30        29
      17        17        16        13                          37        32        31        28
      18        14        17        13                          38        29        32        28
      19        15        17        14                          39        30        32        29
      20        15        18        17                          40        30        33        32
```

Test 11: SPHERICAL FLOW

test #: DFTC11 (SPHERE)

command file: DFTC11.CFI (SPHER.CFI)

grid file: DFTC11.GRF (SPHER.GRF)

output file: DFTC11.OUT (SPHER.OUT)

date of test execution: July 8, 1999

title: Steady-state spherical flow away from a point source in a three-dimensional infinite space.

description: Steady-state flow away from an injection well with an infinite small screen located in the center of a three-dimensional infinite domain; the recharge rate is held constant; the aquifer is isotropic, homogeneous and confined.

tested functions: Fully three-dimensional steady-state flow under confined conditions (i.e., symmetrical flow); fixed head condition at the lateral, top and bottom boundaries; recharging well with constant flux; mass balance calculations.

model domain: *Analytical solution*: the model domain is the three-dimensional infinite space centered around the point well; *numerical model*: the model domain is the cubical positive X-, Y- and Z-space, bounded at a distance of 104 ft in the three principal directions; the well is located in the origin of the coordinate system.

boundary conditions: Fixed head at the outer boundary as read from a file, reflecting effects of non-infinite boundary; fixed injection rate at well node is 400 ft^3/d.

benchmark: Analytical solution of the form (Strack 1990, p. 215):

$$H = Q_0 / 4\pi K R_d + H_i/K \quad \text{with} \quad R_d = \sqrt{X^2 + Y^2 + Z^2}$$

H_i = initial condition; K = hydraulic conductivity; Q_0 = pumping rate

grid: Twelve-layer grid with thirteen levels spaced in the same fashion as the x- and y-grid (see figure B11-1 and table B11-1); in plan view, the grid consists of 115 nodes defining 186 elements (see file DFTC11.GRF or SPHER.GRF).

initial conditions: Read from file DFTC11.HDS.

time-stepping: n.a. (steady-state).

system parameters: $k_x = k_y = k_z = 1.0$ ft/d; [specific storativity = 0.0 ft^{-1}; aquifer specific yield = 0.00; not used in steady-state].

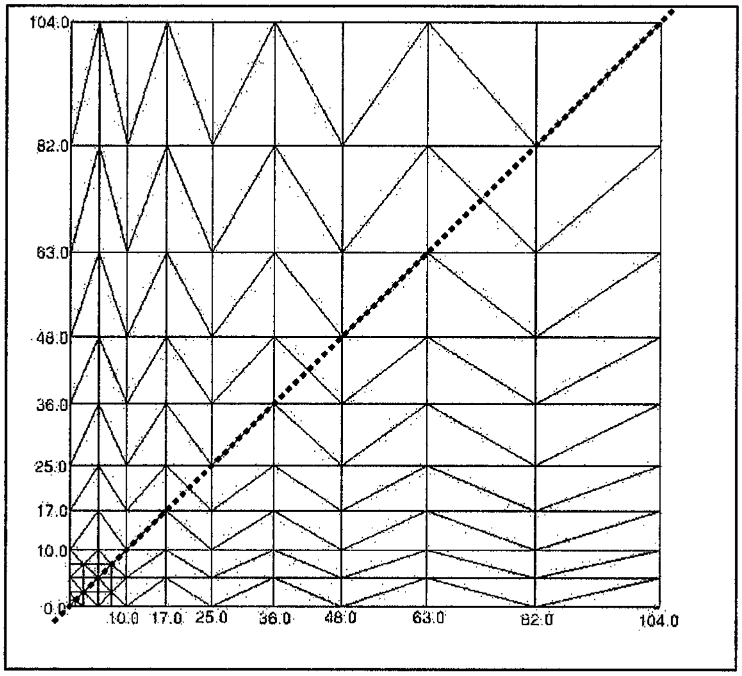


Figure B11-1. Horizontal grid definition (X - Y plane).

Table B11-1. Vertical grid definition (Z direction).

Level	Z-coordinate	Level	Z-coordinate
1	0.0	2	1.0
3	2.5	4	5.0
5	7.5	6	10.0
7	17.0	8	25.0
9	36.0	10	48.0
11	63.0	12	82.0
13	104.0		

verification points: The main verification points are in the vertical plane located at 45° from the X- and Y-axis (see hatched line in figure B11-1). Additional check points are located in the X-Z and Y-Z planes (see table B11-2). The latter check points are compared with equivalent points in the X-Y plane for asymmetrical tendencies.

Table B11-2. Coordinates of comparison nodes.

Node number	X-coordinate	Y-coordinate	Comments
2	0.0	5.0	symmetry check at level 4
4	0.0	17.0	symmetry check at level 7
8	0.0	63.0	symmetry check at level 11
11	5.0	0.0	symmetry check at level 4
12	5.0	5.0	bench mark check at all levels
31	17.0	0.0	symmetry check at level 7
34	17.0	17.0	bench mark check at all levels
71	63.0	0.0	symmetry check at level 11
78	63.0	63.0	bench mark check at all levels
101	2.5	2.5	bench mark check at all levels
102	2.5	0.0	symmetry check at level 3
103	0.0	2.5	symmetry check at level 3
113	1.0	1.0	bench mark check at all levels
114	0.0	1.0	symmetry check at level 2
115	1.0	0.0	symmetry check at level 2

control parameters: Tolerance = 0.001 ft; alpha = 1.5 (relaxation factor); max. # inner iterations = 50.

solver: ICCG

test performed by: Problem set up for numerical code prepared by code developers; code test run and benchmark comparison made by test report author.

type of comparison: Tabular listing of heads (see Table B11-3) and graphical comparison of relative differentials (i.e., difference between DYNFLOW result and bench mark divided by bench mark value; see Figure B11-2); no statistical measures calculated.

Table B11-3. Comparison of results from DYNFLOW with bench mark.

Level	Node	Distance	Bench Mark	DYNFLOW	Difference (DYNFLOW-bench mark)
1	113	1.41	22.51	20.02	-2.48
2	113	1.73	18.38	15.45	-2.92
3	113	2.87	11.08	9.98	-1.10
4	113	5.20	6.13	5.87	-0.25
5	113	7.63	4.17	4.02	-0.15
6	113	10.10	3.15	2.99	-0.17
7	113	17.06	1.87	1.85	-0.01
8	113	25.04	1.27	1.28	0.01
9	113	36.03	0.88	0.90	0.01
10	113	48.02	0.66	0.67	0.01
11	113	63.02	0.51	0.51	0.01
12	113	82.01	0.39	0.39	0.01
13	113	104.01	0.31	0.31	0.00
1	101	3.54	9.00	8.58	-0.43
2	101	3.67	8.66	8.19	-0.48
3	101	4.33	7.35	6.91	-0.44
4	101	6.12	5.20	5.00	-0.19
5	101	8.29	3.84	3.72	-0.12
6	101	10.61	3.00	2.86	-0.14
7	101	17.36	1.83	1.83	-0.01
8	101	25.25	1.26	1.27	0.01
9	101	36.17	0.88	0.89	0.01
10	101	48.13	0.66	0.67	0.01
11	101	63.10	0.50	0.51	0.01
12	101	82.08	0.39	0.39	0.01
13	101	104.06	0.31	0.31	0.00

Level	Node	Distance	Bench Mark	DYNFLOW	Difference (DYNFLOW-bench mark)
1	12	7.07	4.50	4.42	-0.09
2	12	7.14	4.46	4.35	-0.11
3	12	7.50	4.24	4.11	-0.14
4	12	8.66	3.68	3.51	-0.16
5	12	10.31	3.09	2.96	-0.13
6	12	12.25	2.60	2.51	-0.09
7	12	18.41	1.73	1.71	-0.02
8	12	25.98	1.23	1.23	0.00
9	12	36.69	0.87	0.88	0.01
10	12	48.52	0.66	0.67	0.01
11	12	63.40	0.50	0.51	0.01
12	12	82.30	0.39	0.39	0.01
13	12	104.24	0.31	0.30	0.00
1	34	24.04	1.32	1.30	-0.02
2	34	24.06	1.32	1.30	-0.02
3	34	24.17	1.32	1.30	-0.02
4	34	24.56	1.30	1.28	-0.02
5	34	25.18	1.26	1.25	-0.01
6	34	26.04	1.22	1.21	-0.01
7	34	29.44	1.08	1.07	-0.01
8	34	34.68	0.92	0.91	-0.01
9	34	43.29	0.74	0.73	0.00
10	34	53.68	0.59	0.60	0.00
11	34	67.43	0.47	0.48	0.01
12	34	85.45	0.37	0.38	0.00
13	34	106.74	0.30	0.30	0.00
1	78	89.10	0.36	0.36	0.00
2	78	89.10	0.36	0.36	0.00
3	78	89.13	0.36	0.36	0.00
4	78	89.24	0.36	0.36	0.00
5	78	89.41	0.36	0.36	0.00
6	78	89.65	0.36	0.36	0.00
7	78	90.70	0.35	0.35	0.00
8	78	92.54	0.34	0.35	0.00
9	78	96.09	0.33	0.34	0.00
10	78	101.20	0.31	0.32	0.01
11	78	109.12	0.29	0.30	0.01
12	78	121.09	0.26	0.27	0.01
13	78	136.95	0.23	0.23	0.00

iterations: 37

Water balance error: 0.00%

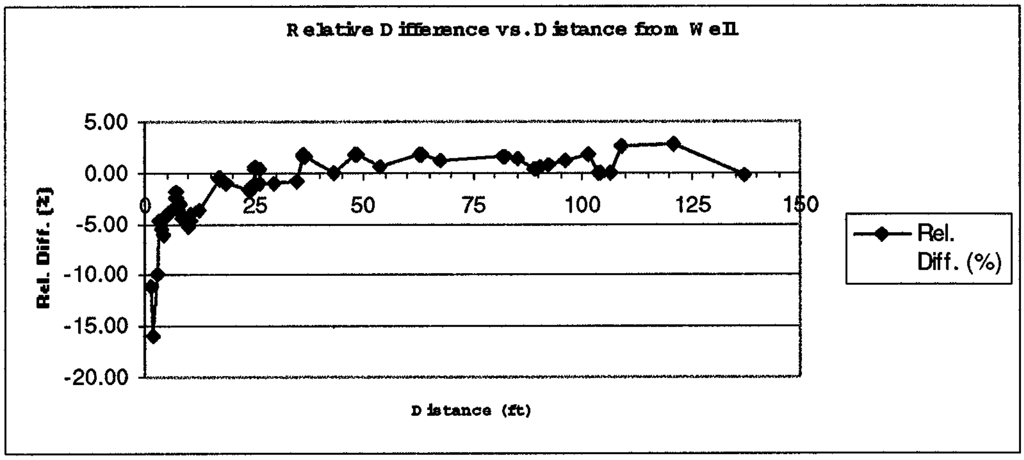


Figure B11-2. Relative differentials versus distance from well in verification plane.

Table B11-4. Evaluation of symmetry of results from DYNFLOW.

node [level]	71 [11]	8 [11]	78 [1]	bench mark
head	0.37	0.36	0.36	0.36
node [level]	4 [7]	31 [7]	34 [1]	bench mark
head	1.29	1.35	1.30	1.32
node [level]	2 [4]	11 [4]	12 [1]	bench mark
head	4.19	4.54	4.42	4.50
node [level]	102 [3]	103 [3]	101 [1]	bench mark
head	8.69	8.11	8.58	9.00
node [level]	115 [2]	114 [2]	113 [1]	bench mark
head	21.89	16.82	20.02	22.51

Performance notes: For short distance from the well (less than 15 ft), the comparison between DYNFLOW and the bench mark show increased values for the relative differentials (see Fig. B11-2). The accuracy can be improved by refining the grid near the well. Also, an asymmetrical effect appears to occur near the domain boundaries, especially in the vicinity of the well where gradients are highest. Reducing the tolerance an order of magnitude does not make a difference, only grid refining does. Selection of solver type may also affect this behavior.

Command File DFTC11.CFI

```
OUTPUT DFTC11.OUT
!
TITLE
DYNFLOW VERIFICATION CASE NO. 11  -- SPHERICAL FLOW
STEADY STATE FLOW TOWARDS A CONSTANT PUMPING POINT
RUN BY PVDH, BOULDER, CO
!
! READ IN GRID
GRID  read DFTC11.GRF form
!
! SPECIFY NUMBER OF LEVELS AND LEVEL ELEVATIONS
LEVE 13.
ELEV 0.0 level 1
ELEV 1.0 LEVEL 2
ELEV 2.5 LEVEL 3
ELEV 5.0 LEVEL 4
ELEV 7.5 LEVEL 5
ELEV 10. LEVEL 6
ELEV 17. LEVEL 7
ELEV 25. LEVEL 8
ELEV 36. LEVEL 9
ELEV 48. LEVEL 10
ELEV 63. LEVEL 11
ELEV 82. LEVEL 12
ELEV 104. LEVEL 13
!
! SPECIFY PROPERTIES AND ASSIGN TO LAYERS
PROP
1,1.0,1.0,1.0,0,0,0
ELEM  301. LAYER ALL ELEM ALL
!
! READ IN STARTING HEADS
head read DFTC11.HDS
HEAD 1000. ADD
!
! ASSIGN BOUNDARY CONDITIONS
FREE
! fIX LATERAL BOUNDARY NODES
fix level all node &
10,20,30,40,50,60,70,80,90,100, &
91,92,93,94,95,96,97,98,99,
! FIX HEADS AT TOP OF MODEL
fix level 13 node all
! ASSIGN PUMPING
flux 50. level 1 node 1
!
DT
TOL   .001
ALPHA 1.5
ITIN  50.
ITER   30.
GOTIL
```

```
! CHECK SIMULATED HEADS AGAINST STARTING HEADS
head 1000. subt
head show node 113
head show node 101
head show node 12
head show node 34
head show node 78
end
```

Grid File DFTC11.GRF

```
     115       186

       1     0.000     0.000
       2     0.000     5.000
       3     0.000     10.00
       4     0.000     17.00
       5     0.000     25.00
       6     0.000     36.00
       7     0.000     48.00
       8     0.000     63.00
       9     0.000     82.00
      10     0.000     104.0
      11     5.000     0.000
      12     5.000     5.000
      13     5.000     10.00
      14     5.000     17.00
      15     5.000     25.00
      16     5.000     36.00
      17     5.000     48.00
      18     5.000     63.00
      19     5.000     82.00
      20     5.000     104.0
      21     10.00     0.000
      22     10.00     5.000
      23     10.00     10.00
      24     10.00     17.00
      25     10.00     25.00
      26     10.00     36.00
      27     10.00     48.00
      28     10.00     63.00
      29     10.00     82.00
      30     10.00     104.0
      31     17.00     0.000
      32     17.00     5.000
      33     17.00     10.00
      34     17.00     17.00
      35     17.00     25.00
      36     17.00     36.00
      37     17.00     48.00
      38     17.00     63.00
      39     17.00     82.00
      40     17.00     104.0
      41     25.00     0.000
      42     25.00     5.000
      43     25.00     10.00
      44     25.00     17.00
      45     25.00     25.00
      46     25.00     36.00
      47     25.00     48.00
      48     25.00     63.00
      49     25.00     82.00
      50     25.00     104.0
      51     36.00     0.000
      52     36.00     5.000
      53     36.00     10.00
      54     36.00     17.00
      55     36.00     25.00
      56     36.00     36.00
      57     36.00     48.00
      58     36.00     63.00
      59     36.00     82.00
      60     36.00     104.0
      61     48.00     0.000
      62     48.00     5.000
      63     48.00     10.00
      64     48.00     17.00
      65     48.00     25.00
      66     48.00     36.00
      67     48.00     48.00
      68     48.00     63.00
      69     48.00     82.00
      70     48.00     104.0
      71     63.00     0.000
      72     63.00     5.000
      73     63.00     10.00
      74     63.00     17.00
      75     63.00     25.00
      76     63.00     36.00
      77     63.00     48.00
      78     63.00     63.00
      79     63.00     82.00
      80     63.00     104.0
      81     82.00     0.000
      82     82.00     5.000
      83     82.00     10.00
      84     82.00     17.00
      85     82.00     25.00
      86     82.00     36.00
      87     82.00     48.00
      88     82.00     63.00
      89     82.00     82.00
      90     82.00     104.0
      91     104.0     0.000
      92     104.0     5.000
      93     104.0     10.00
      94     104.0     17.00
      95     104.0     25.00
      96     104.0     36.00
      97     104.0     48.00
      98     104.0     63.00
      99     104.0     82.00
     100     104.0     104.0
     101     2.500     2.500
     102     2.500     0.000
     103     0.000     2.500
     104     7.500     2.500
     105     7.500     7.500
     106     2.500     7.500
     107     7.500     0.000
     108     0.000     7.500
     109     2.500     5.000
     110     5.000     2.500
```

```
  111     5.000     7.500
  112     7.500     5.000
  113     1.000     1.000
  114     0.000     1.000
  115     1.000     0.000
```

```
    2        12       109       101
    4        13         3       106
    5         3        14         4
    6         3        13        14
    7         4        15         5
    8         4        14        15
    9         5        16         6
   10         5        15        16
   11         6        17         7
   12         6        16        17
   13         7        18         8
   14         7        17        18
   15         8        19         9
   16         8        18        19
   17         9        20        10
   18         9        19        20
   19       104        12       110
   20        22       112       104
   21       105        13       111
   22        23        13       105
   23        13        23        14
   24        23        24        14
   25        14        24        15
   26        24        25        15
   27        15        25        16
   28        25        26        16
   29        16        26        17
   30        26        27        17
   31        17        27        18
   32        27        28        18
   33        18        28        19
   34        28        29        19
   35        19        29        20
   36        29        30        20
   37        21        32        22
   38        21        31        32
   39        22        33        23
   40        22        32        33
   41        23        34        24
   42        23        33        34
   43        24        35        25
   44        24        34        35
   45        25        36        26
   46        25        35        36
   47        26        37        27
   48        26        36        37
   49        27        38        28
   50        27        37        38
   51        28        39        29
   52        28        38        39
   53        29        40        30
   54        29        39        40
   55        31        41        32
   56        41        42        32
   57        32        42        33
   58        42        43        33
   59        33        43        34
   60        43        44        34
   61        34        44        35
   62        44        45        35
   63        35        45        36
   64        45        46        36
   65        36        46        37
   66        46        47        37
   67        37        47        38
   68        47        48        38
   69        38        48        39
   70        48        49        39
   71        39        49        40
   72        49        50        40
```

```
   73      41      52      42            143      79      89      80
   74      41      51      52            144      89      90      80
   75      42      53      43            145      81      92      82
   76      42      52      53            146      81      91      92
   77      43      54      44            147      82      93      83
   78      43      53      54            148      82      92      93
   79      44      55      45            149      83      94      84
   80      44      54      55            150      83      93      94
   81      45      56      46            151      84      95      85
   82      45      55      56            152      84      94      95
   83      46      57      47            153      85      96      86
   84      46      56      57            154      85      95      96
   85      47      58      48            155      86      97      87
   86      47      57      58            156      86      96      97
   87      48      59      49            157      87      98      88
   88      48      58      59            158      87      97      98
   89      49      60      50            159      88      99      89
   90      49      59      60            160      88      98      99
   91      51      61      52            161      89     100      90
   92      61      62      52            162      89      99     100
   93      52      62      53            164      11     110     101
   94      62      63      53            165     101     113     102
   95      53      63      54            166      11     101     102
   96      63      64      54            168       2     103     101
   97      54      64      55            170      21      22     104
   98      64      65      55            171     105      12     112
   99      55      65      56            172      22      23     105
  100      65      66      56            173     106       2     109
  101      56      66      57            174      12     111     106
  102      66      67      57            175     104      11     107
  103      57      67      58            176      21     104     107
  104      67      68      58            177     108       2     106
  105      58      68      59            178       3     108     106
  106      68      69      59            179      12     106     109
  107      59      69      60            180       2     101     109
  108      69      70      60            181      11     104     110
  109      61      72      62            182      12     101     110
  110      61      71      72            183      12     105     111
  111      62      73      63            184      13     106     111
  112      62      72      73            185      22     105     112
  113      63      74      64            186      12     104     112
  114      63      73      74            187     101     103     113
  115      64      75      65            188     113       1     115
  116      64      74      75            189     113     115     102
  117      65      76      66            190     114       1     113
  118      65      75      76            191     103     114     113
  119      66      77      67
  120      66      76      77
  121      67      78      68
  122      67      77      78
  123      68      79      69
  124      68      78      79
  125      69      80      70
  126      69      79      80
  127      71      81      72
  128      81      82      72
  129      72      82      73
  130      82      83      73
  131      73      83      74
  132      83      84      74
  133      74      84      75
  134      84      85      75
  135      75      85      76
  136      85      86      76
  137      76      86      77
  138      86      87      77
  139      77      87      78
  140      87      88      78
  141      78      88      79
  142      88      89      79
```

Results File DFTC11.OUT (reformatted)

```
>>>>> THIS PROGRAM IS THE CONFIDENTIAL AND PROPRIETARY INFORMATION OF      <<<<<
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--- THIS RUN OF DYNFLOW5
--- VERSION 5.18E      (ICCG SOLVER)  SEPT. 1996
--- STARTED AT   7/15/99 11:56:20.
--- ALL OUTPUT WILL BE TAGGED WITH THIS DATE/TIME.





!
TITLE

ENTER THREE TITLE LINES ("!" FOR NO CHANGE) :
TITLE LINE #1 :
TITLE LINE #2 :
TITLE LINE #3 :

HERE IS HOW THE TITLE LINES LOOK --
DYNFLOW VERIFICATION CASE NO. 11  -- SPHERICAL FLOW
STEADY STATE FLOW TOWARDS A CONSTANT PUMPING POINT
RUN BY PVDH, BOULDER, CO

!
! READ IN GRID
GRID  read DFTC11.GRF form

GRID INFO. NOW BEING PROCESSED ...

--- GRID DATA NOW BEING CLEARED,
--- PRIOR TO FILE READING.

*** ERRORS OR WARNINGS DURING PROCESSING OF
***    ELEMENT GRID INFORMATION.
*** A VALUE OF -9999 INDICATES THAT THE PARAMETER
***    IS NOT A PROBLEM, OR IT WAS NOT COMPUTED,
***    POSSIBLY DUE TO A PREVIOUS PROBLEM.
*** NOTE THE FOLLOWING:
***    MAX. EXTERNAL ELEMENT NO. ....... : 10000
***    MAX. EXTERNAL NODE    NO. ....... : *****
***    ELEM SIDE RATIO WARNING LIMIT ... :   3.000
***    ELEM SIDE RATIO ERROR   LIMIT ... :   6.000
*** ALSO, ELEMENT AREA FOR NON 1-D ELEMENTS
***    IS NOT ALLOWED TO BE ZERO OR BELOW.
*** LIST OF PARAMETERS FOR ELEMENTS WITH WARNINGS
***    AND/OR ERRORS IS AS FOLLOWS :

*** WARNING,   ELEM NOS    EXT ELEM NO     CONNECTED NODES      SIDE LENGTH RATIOS
*** ERROR,      ON FILE    -----------     ---------------      ------------------    HORIZONTAL
*** 1D ELEM    --------   BEYOND  IN USE   NODE  NODE  NODE    SIDE    SIDE    SIDE     SURFACE
***            INT   EXT  RANGE   AT INT    #1    #2    #3   1-3/2-3 1-2/1-3 1-2/2-3     AREA
*** --------   ---   ---  ------  ------   ----  ----  ----  ------- ------- -------  ----------
*** WARNING    11    13                                                        3.16
*** WARNING    12    14                                                3.16
*** WARNING    13    15                                        3.80            3.93
*** WARNING    14    16                                                3.93    3.80
*** WARNING    15    17                                        4.40            4.51
*** WARNING    16    18                                                4.51    4.40
*** WARNING    29    31                                                        3.16
*** WARNING    30    32                                        3.16
```

```
*** WARNING    31    33                                                3.80    3.93
*** WARNING    32    34                                        3.93            3.80
*** WARNING    33    35                                                4.40    4.51
*** WARNING    34    36                                        4.51            4.40
*** WARNING    51    53                                        3.14            3.30
*** WARNING    52    54                                                3.30    3.14
*** WARNING   107   109                                                3.16
*** WARNING   108   110                                        3.16
*** WARNING   109   111                                                3.16
*** WARNING   110   112                                        3.16
*** WARNING   125   127                                        3.93    3.80
*** WARNING   126   128                                                3.93    3.80
*** WARNING   127   129                                        3.93    3.80
*** WARNING   128   130                                                3.93    3.80
*** WARNING   143   145                                        4.40    4.51
*** WARNING   144   146                                        4.51            4.40
*** WARNING   145   147                                        4.40    4.51
*** WARNING   146   148                                        4.51            4.40
*** WARNING   147   149                                        3.14    3.30
*** WARNING   148   150                                        3.30            3.14

--- GRID WAS PROCESSED OK.

*** WRITING GRID DATA TO FILE "GRID.SUM"

!
! SPECIFY NUMBER OF LEVELS AND LEVEL ELEVATIONS
LEVE 13.
ELEV 0.0 level 1
ELEV 1.0 LEVEL 2
ELEV 2.5 LEVEL 3
ELEV 5.0 LEVEL 4
ELEV 7.5 LEVEL 5
ELEV 10. LEVEL 6
ELEV 17. LEVEL 7
ELEV 25. LEVEL 8
ELEV 36. LEVEL 9
ELEV 48. LEVEL 10
ELEV 63. LEVEL 11
ELEV 82. LEVEL 12
ELEV 104. LEVEL 13
!
! SPECIFY PROPERTIES AND ASSIGN TO LAYERS
PROP

ENTER PROPERTIES IN FOLLOWING ORDER --
#,KXX,KYY,KZZ,STORATIVITY,SPEC. YIELD,RECHARGE,THETA,PHI,SPEC. GRAV.,EFF. STRESS:
1,1.0,1.0,1.0,0,0,0
ELEM  301. LAYER ALL ELEM ALL
!
! READ IN STARTING HEADS
head read DFTC11.HDS
HEAD 1000. ADD
!
! ASSIGN BOUNDARY CONDITIONS
FREE
! fIX LATERAL BOUNDARY NODES
fix level all node &
10,20,30,40,50,60,70,80,90,100, &
91,92,93,94,95,96,97,98,99,
! FIX HEADS AT TOP OF MODEL
fix level 13 node all
! ASSIGN PUMPING
flux 50. level 1 node 1
!
DT
TOL   .0001
ALPHA 1.5
ITIN  50.
ITER   30.
```

```
 GOTIL
  *** I.C.C.G. SOLVER SELECTED

 CG  HAS CONVERGED IN    37 ITERATIONS
1*********** DYNFLOW5    *********** VERSION 5.18E    (ICCG SOLVER)  SEPT. 1996
*********** DYNFLOW5    ************
 *********.....DYNFLOW VERIFICATION CASE NO. 11  -- SPHERICAL FLOW
..... RUN DATE :  7/15/99    *********
 *********.....STEADY STATE FLOW TOWARDS A CONSTANT PUMPING POINT
..... RUN TIME : 11:56:20    *********
 *********.....RUN BY PVDH, BOULDER, CO
.....                        *********
 ***************************************************************************************************
 *** ALL 13 LEVELS  *** TIME       .00000 ** TIME STEP   1 *** TIME STEP DURATION       .00000 ***
0 ITERATIONS (30 MAX) **********

 MODEL SIZE
 ==========
 NODES  ELEMENTS  LEVELS  LAYERS
 -----  --------  ------  ------
   115     186      13      12


 PROPERTY SETS
 =============
     ---------- HYDRAULIC CONDUCTIVITIES -------                    SPECIFIC
NO.  HORIZONTAL-X    HORIZONTAL-Y     VERTICAL-Z   STORATIVITY    YIELD    RECHARGE  THETA
 ---  ------------    ------------     ----------  -----------    -----    --------  -----
1       1.0000000       1.0000000       1.0000000  .0000E+00    .00000   .0000000    .00

 PH     UNIT     EFFECT.   # OF
       WEIGHT     STRESS   ELEMS  NO.
 --    ------     ------   -----  ---
.00    .0000      .0000  2232     1



 *******************************************************
 * CONDITIONAL BOUNDARIES (See Node List Table Above) *
 *******************************************************

 NO. OF INVOKED RISING WATER NODES:          0
 NO. OF INVOKED DRY NODES:                   0
 NO. OF RISING WATER NODES BELOW TOP
   OF MODEL (CODE = *RISI*)                  0



 *********** DYNFLOW5    *********** VERSION 5.18E    (ICCG SOLVER)  SEPT. 1996
 *********.....DYNFLOW VERIFICATION CASE NO. 11  -- SPHERICAL FLOW
..... RUN DATE :  7/15/99    *********
 *********.....STEADY STATE FLOW TOWARDS A CONSTANT PUMPING POINT
..... RUN TIME : 11:56:20    *********
 *********.....RUN BY PVDH, BOULDER, CO
.....                        *********

***************************************************************************************************
 *** ALL 13 LEVELS  *** TIME       .00000 ** TIME STEP   1 *** TIME STEP DURATION       .00000
***  0 ITERATIONS (30 MAX) **********

                               MASS BALANCE TABLE
                               ==================

          FOR THE ENTIRE SYSTEM OF  13 LEVELS AND  115 NODES
          ==================================================

            LEVEL          TOTAL    FIXED HEAD        PUMPING       RECHARGE        STORAGE
             NO.            FLUX       FLUX             FLUX          FLUX            FLUX
```

```
            -----          -----     ----------        -------       --------       -------
 INFLOWS        1         50.000           .000         50.000           .000          .000
                2           .001           .001           .000           .000          .000
                3           .046           .046           .000           .000          .000
                4           .000           .000           .000           .000          .000
                5           .000           .000           .000           .000          .000
                6           .000           .000           .000           .000          .000
                7           .000           .000           .000           .000          .000
                8           .332           .332           .000           .000          .000
                9          2.059          2.059           .000           .000          .000
               10          5.725          5.725           .000           .000          .000
               11         13.940         13.940           .000           .000          .000
               12         34.458         34.458           .000           .000          .000
               13           .856           .856           .000           .000          .000
            TOTAL        107.420         57.420         50.000           .000          .000

 OUTFLOWS       1          -.211          -.211           .000           .000          .000
                2          -.613          -.613           .000           .000          .000
                3          -.598          -.598           .000           .000          .000
                4         -1.576         -1.576           .000           .000          .000
                5         -1.268         -1.268           .000           .000          .000
                6         -2.083         -2.083           .000           .000          .000
                7         -3.571         -3.571           .000           .000          .000
                8         -4.589         -4.589           .000           .000          .000
                9         -6.697         -6.697           .000           .000          .000
               10        -10.345        -10.345           .000           .000          .000
               11        -18.369        -18.369           .000           .000          .000
               12        -31.669        -31.669           .000           .000          .000
               13        -25.830        -25.830           .000           .000          .000
            TOTAL       -107.420       -107.420           .000           .000          .000

 NET FLUX       1         49.789          -.211         50.000           .000          .000
                2          -.612          -.612           .000           .000          .000
                3          -.552          -.552           .000           .000          .000
                4         -1.575         -1.575           .000           .000          .000
                5         -1.268         -1.268           .000           .000          .000
                6         -2.083         -2.083           .000           .000          .000
                7         -3.571         -3.571           .000           .000          .000
                8         -4.257         -4.257           .000           .000          .000
                9         -4.638         -4.638           .000           .000          .000
               10         -4.620         -4.620           .000           .000          .000
               11         -4.429         -4.429           .000           .000          .000
               12          2.789          2.789           .000           .000          .000
               13        -24.974        -24.974           .000           .000          .000
            TOTAL           .000        -50.000         50.000           .000          .000


 MASS BALANCE ERROR        .00 %

 REJECTED RECHARGE, NODAL POINT BASIS :             .00
 REJECTED RECHARGE, ELEMENT BASIS     :             .00

 *********** DYNFLOW5   *********** VERSION 5.18E    (ICCG SOLVER)  SEPT. 1996
 *********.....DYNFLOW VERIFICATION CASE NO. 11  -- SPHERICAL FLOW
..... RUN DATE :  7/15/99    *********
 *********.....STEADY STATE FLOW TOWARDS A CONSTANT PUMPING POINT
..... RUN TIME : 11:56:20    *********
 *********.....RUN BY PVDH, BOULDER, CO
.....                        *********

**********************************************************************************************
 *** ALL 13 LEVELS  *** TIME       .00000 ** TIME STEP   1 *** TIME STEP DURATION       .00000
***  0 ITERATIONS (30 MAX) **********


 SELECTED UNIT-SPECIFIC INFORMATION, ASSUMING FEET-DAY UNITS USED IN MODEL
 ========================================================================

 GRID AREA                        =        10816.0 (SQ. FT.)
                                  =           .000 (SQ. MI.)
```

```
NET TOTAL ELEMENT RECHARGE     =         .00000 (FT./DAY)
                               =            .00 (INCHES/YEAR)
                               =           .000 (MGD/SQ.MI.)

FIXED HEAD DISCHARGE (OUTFLOW) =        -.00462 (FT./DAY)
                               =         -20.25 (INCHES/YEAR)
                               =          -.964 (MGD/SQ.MI.)

FIXED HEAD  RECHARGE ( INFLOW) =          .0007 (CFS)
FIXED HEAD DISCHARGE (OUTFLOW) =         -.0012 (CFS)
FIXED HEAD FLUX    (NET INFLOW) =        -.0006 (CFS)

PUMPING  RECHARGE ( INFLOW)    =             .3 (GPM)
PUMPING DISCHARGE (OUTFLOW)    =             .0 (GPM)
PUMPING FLUX    (NET INFLOW)   =             .3 (GPM)

PUMPING  RECHARGE ( INFLOW)    =           .000 (MGD)
PUMPING DISCHARGE (OUTFLOW)    =           .000 (MGD)
PUMPING FLUX    (NET INFLOW)   =           .000 (MGD)


VOLUMES
=======

LAYER               MEDIA                WATER
-----               -----                -----
    1           10816.020                 .000
    2           16224.000                 .000
    3           27039.960                 .000
    4           27039.960                 .000
    5           27039.960                 .000
    6           75711.810                 .000
    7           86528.130                 .000
    8          118976.200                 .000
    9          129792.000                 .000
   10          162240.000                 .000
   11          205504.300                 .000
   12          237952.300                 .000
TOTAL         1124865.000                 .000
! CHECK SIMULATED HEADS AGAINST STARTING HEADS
head 1000. subt

head show node 113

    1,    113,  20.02307     ,  .0000000
    2,    113,  15.45276     ,  .0000000
    3,    113,  9.980225     ,  .0000000
    4,    113,  5.873169     ,  .0000000
    5,    113,  4.020508     ,  .0000000
    6,    113,  2.986694     ,  .0000000
    7,    113,  1.852722     ,  .0000000
    8,    113,  1.276489     ,  .0000000
    9,    113,  .8978271     ,  .0000000
   10,    113,  .6742554     ,  .0000000
   11,    113,  .5141602     ,  .0000000
   12,    113,  .3944092     ,  .0000000
   13,    113,  .3060303     ,  .0000000


head show node 12

    1,     12,  4.416321     ,  .0000000
    2,     12,  4.345276     ,  .0000000
    3,     12,  4.105103     ,  .0000000
    4,     12,  3.512207     ,  .0000000
    5,     12,  2.960571     ,  .0000000
    6,     12,  2.505432     ,  .0000000
    7,     12,  1.711792     ,  .0000000
    8,     12,  1.228394     ,  .0000000
```

```
head show node 101

    1,    101,  8.577759     ,  .0000000
    2,    101,  8.185730     ,  .0000000
    3,    101,  6.908691     ,  .0000000
    4,    101,  5.003235     ,  .0000000
    5,    101,  3.721069     ,  .0000000
    6,    101,  2.859131     ,  .0000000
    7,    101,  1.826172     ,  .0000000
    8,    101,  1.267700     ,  .0000000
    9,    101,  .8949585     ,  .0000000
   10,    101,  .6729736     ,  .0000000
   11,    101,  .5136108     ,  .0000000
   12,    101,  .3941650     ,  .0000000
   13,    101,  .3060303     ,  .0000000


    9,     12,  .8805542     ,  .0000000
   10,     12,  .6671143     ,  .0000000
   11,     12,  .5110474     ,  .0000000
   12,     12,  .3930054     ,  .0000000
   13,     12,  .3049927     ,  .0000000
```

```
head show node 34

   1,    34,  1.301270    ,  .0000000
   2,    34,  1.300964    ,  .0000000
   3,    34,  1.296509    ,  .0000000
   4,    34,  1.278992    ,  .0000000
   5,    34,  1.249084    ,  .0000000
   6,    34,  1.209900    ,  .0000000
   7,    34,  1.068787    ,  .0000000
   8,    34,  .9102783    ,  .0000000
   9,    34,  .7348022    ,  .0000000
  10,    34,  .5963745    ,  .0000000
  11,    34,  .4772339    ,  .0000000
  12,    34,  .3773804    ,  .0000000
  13,    34,  .2979736    ,  .0000000
```

```
head show node 78

   1,     78,  .3585815     ,  .0000000
   2,     78,  .3585815     ,  .0000000
   3,     78,  .3584595     ,  .0000000
   4,     78,  .3580933     ,  .0000000
   5,     78,  .3574829     ,  .0000000
   6,     78,  .3566284     ,  .0000000
   7,     78,  .3530884     ,  .0000000
   8,     78,  .3469238     ,  .0000000
   9,     78,  .3354492     ,  .0000000
  10,     78,  .3202515     ,  .0000000
  11,     78,  .2990112     ,  .0000000
  12,     78,  .2703247     ,  .0000000
  13,     78,  .2319946     ,  .0000000
```

```
head show node 2

   1,      2,  6.119263     ,  .0000000
   2,      2,  5.958923     ,  .0000000
   3,      2,  5.342651     ,  .0000000
   4,      2,  4.190125     ,  .0000000
   5,      2,  3.317444     ,  .0000000
   6,      2,  2.685974     ,  .0000000
   7,      2,  1.760681     ,  .0000000
   8,      2,  1.243225     ,  .0000000
   9,      2,  .8847656     ,  .0000000
  10,      2,  .6687622     ,  .0000000
  11,      2,  .5117798     ,  .0000000
  12,      2,  .3933105     ,  .0000000
  13,      2,  .3060303     ,  .0000000
```

```
head show node 4

   1,      4,  1.877563     ,  .0000000
   2,      4,  1.869629     ,  .0000000
   3,      4,  1.844543     ,  .0000000
   4,      4,  1.772156     ,  .0000000
   5,      4,  1.683533     ,  .0000000
   6,      4,  1.587280     ,  .0000000
   7,      4,  1.291626     ,  .0000000
   8,      4,  1.035095     ,  .0000000
   9,      4,  .7951660     ,  .0000000
  10,      4,  .6270752     ,  .0000000
  11,      4,  .4920654     ,  .0000000
  12,      4,  .3839722     ,  .0000000
  13,      4,  .3020020     ,  .0000000
```

```
head show node 8

   1,      8,  .5110474     ,  .0000000
   2,      8,  .5108643     ,  .0000000
   3,      8,  .5103149     ,  .0000000
   4,      8,  .5087891     ,  .0000000
   5,      8,  .5067139     ,  .0000000
   6,      8,  .5041504     ,  .0000000
   7,      8,  .4913940     ,  .0000000
   8,      8,  .4726563     ,  .0000000
   9,      8,  .4412842     ,  .0000000
  10,      8,  .4055786     ,  .0000000
  11,      8,  .3622437     ,  .0000000
  12,      8,  .3127441     ,  .0000000
  13,      8,  .2620239     ,  .0000000
```

```
head show node 11

   1,     11,  6.326294     ,  .0000000
   2,     11,  6.247803     ,  .0000000
   3,     11,  5.684875     ,  .0000000
   4,     11,  4.544189     ,  .0000000
   5,     11,  3.537964     ,  .0000000
   6,     11,  2.779724     ,  .0000000
   7,     11,  1.828979     ,  .0000000
   8,     11,  1.271790     ,  .0000000
   9,     11,  .8977051     ,  .0000000
  10,     11,  .6739502     ,  .0000000
  11,     11,  .5140381     ,  .0000000
  12,     11,  .3944092     ,  .0000000
  13,     11,  .3060303     ,  .0000000
```

```
head show node 31

   1,     31,  1.879150     ,  .0000000
   2,     31,  1.878113     ,  .0000000
   3,     31,  1.864075     ,  .0000000
   4,     31,  1.812073     ,  .0000000
   5,     31,  1.728943     ,  .0000000
   6,     31,  1.628296     ,  .0000000
   7,     31,  1.350037     ,  .0000000
   8,     31,  1.077148     ,  .0000000
   9,     31,  .8246460     ,  .0000000
  10,     31,  .6431885     ,  .0000000
  11,     31,  .5012207     ,  .0000000
  12,     31,  .3892822     ,  .0000000
  13,     31,  .3020020     ,  .0000000
```

```
head show node 71

   1,     71,  .5115967     ,  .0000000
   2,     71,  .5115356     ,  .0000000
   3,     71,  .5113525     ,  .0000000
   4,     71,  .5105591     ,  .0000000
   5,     71,  .5089722     ,  .0000000
   6,     71,  .5066528     ,  .0000000
   7,     71,  .4975586     ,  .0000000
   8,     71,  .4810791     ,  .0000000
   9,     71,  .4518433     ,  .0000000
  10,     71,  .4163818     ,  .0000000
  11,     71,  .3738403     ,  .0000000
  12,     71,  .3265381     ,  .0000000
  13,     71,  .2620239     ,  .0000000
```

```
head show node 102

   1,    102,  13.47302     ,  .0000000
   2,    102,  11.79132     ,  .0000000
   3,    102,  8.692627     ,  .0000000
   4,    102,  5.586609     ,  .0000000
   5,    102,  3.936829     ,  .0000000
   6,    102,  2.951538     ,  .0000000
   7,    102,  1.850891     ,  .0000000
   8,    102,  1.276550     ,  .0000000
   9,    102,  .8982544     ,  .0000000
  10,    102,  .6743164     ,  .0000000
  11,    102,  .5142212     ,  .0000000
  12,    102,  .3944092     ,  .0000000
  13,    102,  .3060303     ,  .0000000
```

```
head show node 103

   1,    103,  12.25073    ,  .0000000
   2,    103,  10.75549    ,  .0000000
   3,    103,  8.112427    ,  .0000000
   4,    103,  5.291199    ,  .0000000
   5,    103,  3.813599    ,  .0000000
   6,    103,  2.918579    ,  .0000000
   7,    103,  1.829834    ,  .0000000
   8,    103,  1.268616    ,  .0000000
   9,    103,  .8947144    ,  .0000000
  10,    103,  .6729736    ,  .0000000
  11,    103,  .5136108    ,  .0000000
  12,    103,  .3941040    ,  .0000000
  13,    103,  .3060303    ,  .0000000
```

```
head show node 114

   1,    114,  25.70203    ,  .0000000
   2,    114,  16.81525    ,  .0000000
   3,    114,  10.09344    ,  .0000000
   4,    114,  5.845642    ,  .0000000
   5,    114,  4.014282    ,  .0000000
   6,    114,  2.989990    ,  .0000000
   7,    114,  1.851685    ,  .0000000
   8,    114,  1.276245    ,  .0000000
   9,    114,  .8977051    ,  .0000000
  10,    114,  .6741943    ,  .0000000
  11,    114,  .5141602    ,  .0000000
  12,    114,  .3943481    ,  .0000000
  13,    114,  .3060303    ,  .0000000
```

```
head show node 115

   1,    115,  36.82239    ,  .0000000
   2,    115,  21.88696    ,  .0000000
   3,    115,  11.60376    ,  .0000000
   4,    115,  6.235718    ,  .0000000
   5,    115,  4.117554    ,  .0000000
   6,    115,  3.010010    ,  .0000000
   7,    115,  1.858826    ,  .0000000
   8,    115,  1.278381    ,  .0000000
   9,    115,  .8984985    ,  .0000000
  10,    115,  .6744995    ,  .0000000
  11,    115,  .5142822    ,  .0000000
  12,    115,  .3944092    ,  .0000000
  13,    115,  .3060303    ,  .0000000
end




******************************************************
* CONDITIONAL BOUNDARIES (See Node List Table Above) *
******************************************************

NO. OF INVOKED RISING WATER NODES:        0
NO. OF INVOKED DRY NODES:                 0
NO. OF RISING WATER NODES BELOW TOP
  OF MODEL (CODE = *RISI*)                0



--- THIS RUN OF DYNFLOW5
--- VERSION 5.18E    (ICCG SOLVER)  SEPT. 1996
--- WHICH STARTED AT  7/15/99 11:56:20

--- IS ENDING AT      7/15/99 11:56:25
```

Test 12 EVAPORATION AND RECHARGE

test #:	DFTC12
command file:	DFTC12.CFI
grid file:	DFTC12.GRF
output file:	DFTC12.OUT
date of test execution:	January 7, 1998
title:	Evaporation and recharge computation.
description:	Steady state horizontal uniform flow between two fully penetrating drains in an isotropic, homogeneous, unconfined aquifer with a horizontal impermeable base (see figure B12-1) modified by recharge and evaporation. The geometry of this model is identical to that of DFTC01A except for the height.

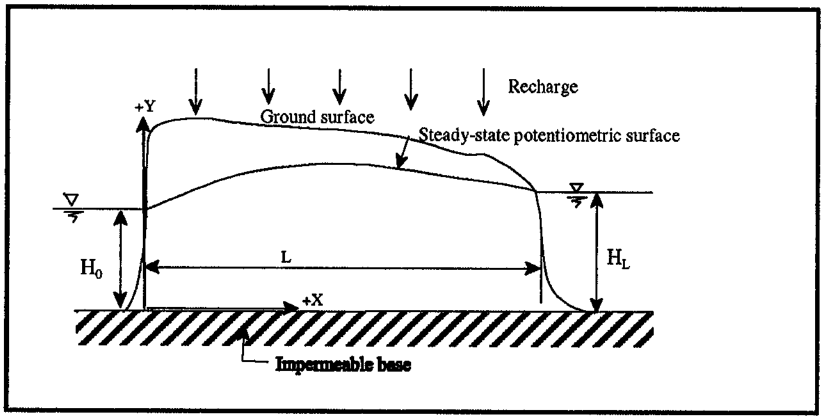

Figure B12-1. Conceptual model for test case DFTC12.

tested functions:	Distributed recharge and evaporation algorithms and their additive use.
model domain:	Strip between two parallel drains with a length, width and thickness of L=100 ft, w=10 ft, and b=80 ft respectively.
boundary conditions:	Constant head at left boundary (x=0 ft) is H_0=50 ft; constant head at right boundary (x=100 ft) is H_L=75 ft; no-flow boundaries in y- and z-direction; free surface on top, no flow boundary at bottom.
benchmark:	The test strategy is two-fold: 1) compare recharge results with analytical solution; 2) check global water balance and local evaporation "by hand".

The analytical solution for uniform recharge is:

$$K (h^2 - H_0^2) - Nx (L - x) + Kx/L (H_0^2 - H_L^2) = 0 \text{ (Bear, 1979)}$$

in which N is the uniform recharge rate [L/T] and K the hydraulic conductivity [L/T].

grid: Two-dimensional horizontal grid with one layer and two levels; in plan view, the grid consists of 33 nodes in three rows, defining 40 elements (see figure B12-2).

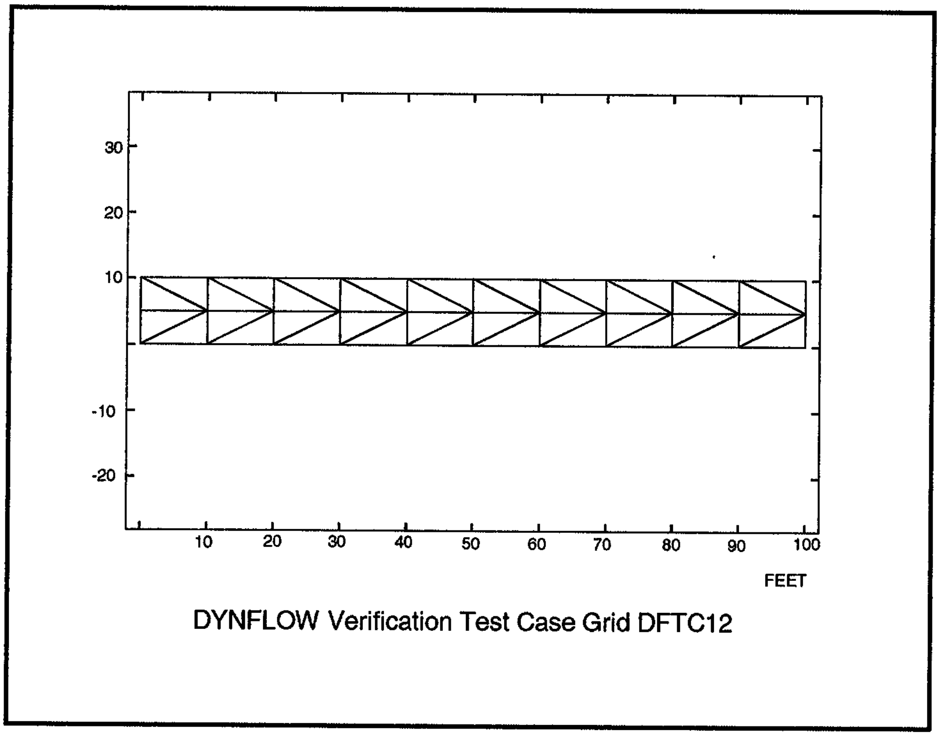

Figure B12-2.

initial conditions: n.a. (steady state)

time-stepping: n.a. (steady state)

system parameters: Hydraulic conductivity $K_x = K_y = 1.0$ ft/d; $= K_z = 100.0$ ft/d

control parameters: Tolerance = 1.0 ft

solver: ICCG

test performed by: Problem set up for numerical code prepared by code developers; code run and benchmark comparison performed by test report author.

type of comparison: Tabular listing of heads (see Table B12-1) and manual water budget calculations (see listing of DFTC12.OUT); no statistical measures calculated.

Table B12-1. Results for recharge N = 0.01 ft/d.

distance from origin (ft)	piezometric head (ft) for average of all nodes at specified distance (see DFTC12-results.xls for details)	
	analytical solution	DYNFLOW
0	50.00	50.00
10	53.12	53.12
20	56.04	56.05
30	58.81	58.81
40	61.43	61.44
50	63.93	63.94
60	66.32	66.33
70	68.62	68.62
80	70.82	70.83
90	72.95	72.95
100	75.00	175.00
total mass balance error	.0006%	

Notes on performance: The comparison for the head is excellent and the water balance calculations show that the relevant algorithms function correctly.

Command File DFTC12.CFI

```
OUTPUT DFTC12.OUT

TITL
VERIFICATION CASE NO. 12 -- EVAPORATION AND RECHARGE
STEADY-STATE UNCONFINED ONE-DIMENSIONAL FLOW WITH RECHARGE AND EVAPORATION
RUN BY PVDH, BOULDER CO.

TEXT
```

```
        THIS TEST CASE DEMONSTRATES THAT APPROPRIATE
        RECHARGE AND EVAPORATION TERMS ARE ADDED TO THE SOLUTION.

ENDT

! INITIAL MODEL SETUP

GRID READ DFTC12.GRF FORMatted
LEVEL  2.
FREE
ELEM 301.
ELEV   0.      LEVELSING     1
ELEV  80.      LEVELSING     2
INIT  75.
INIT  50.      LEVELALL            NODE RANGE    1    3
FIX            LEVELALL            NODE RANGE    1    3
FIX            LEVELALL            NODE RANGE   31   33
DT     0.
TOL   0001.
ITER   100.
PRAL
NOPR

!       THE FIRST CASE SETS THE ELEMENT RECHARGE
!       USING THE ORIGINAL METHOD OF ASSIGNMENT
!       OF RECHARGE THROUGH THE 'PROP' COMMAND.
!       THE GRID AREA IS 1000 FT.SQ. AND THE
!       RECHARGE IS 0.01 FT/D GIVING A TOTAL FLUX
!       OF 10 CFD

PROP
1,1.,1.,100.,0.,0.,0.01,0.,0.

GOTIL 0.

PRIN

!       THE COMPUTED TOTAL RECHARGE SHOWN BELOW SHOULD BE 10 CFD (FIRST LINE).

FLXL LEVEL 2 SUM

!       THE SECOND CASE USES THE 'RECH' COMMAND WITH
!       THE ELEMENT SPECIFICATION. THIS RECHARGE WILL BE ADDED
!       TO THE ORIGINAL VALUE GIVEN THROUGH THE 'PROP' COMMAND
!       TO GIVE A TOTAL OF 20 CFD.

RECH  0.01 ELEM ALL
GOTI  0.

PRIN

!       THE COMPUTED TOTAL RECHARGE SHOWN BELOW SHOULD BE 20 CFD (FIRST LINE).

FLXL LEVEL 2 SUM

!       THE THIRD CASE USES THE 'RECH' COMMAND WITH
!       THE NODE SPECIFICATION. THE NUMBER OF NODES IS
!       33 SO THAT THE TOTAL RECHARGE WILL NOW BE
!       43 CFD (10 + 33*1.0). NOTE THAT THE 'RECH' COMMAND
!       REPLACES THE ORIGINAL VALUES SET BY THE 'RECH'
!       COMMAND BEFORE.

RECH  1.0 NODE ALL
GOTI  0.

PRIN

!       THE COMPUTED TOTAL RECHARGE SHOWN BELOW SHOULD BE 43 CFD (FIRST LINE).
```

```
FLXL LEVEL 2 SUM

!       THE FOURTH CASE USES THE 'EVAP' COMMAND FOR ALL NODES.
!       TO CHECK ITS OPERATION, THE RECHARGE AT NODE 29 (LOCATED ALONG THE
!       CENTER AXIS OF THE GRID) WITH NO EVAPORATION SHOULD BE 1.5 CFD.
!       THE RECHARGE AT NODE 29 WITH EVAPORATION SHOULD BE 1.3424 CFD.

!       RECHARGE AT NODE 29 WITHOUT EVAPORATION SHOWN BELOW SHOULD EQUAL 1.5 CFD.

FLXL LEVEL 2 NODE 29 SHOW

EVAP 0.01 DEPTH  10. ELEM ALL
GOTI

!       RECHARGE AT NODE 29 WITH ET SHOWN BELOW SHOULD BE 1.3424 CFD.

FLXL LEVEL 2 NODE 29 SHOW

!       THE ALGEBRAIC SUM OF THE EVAPORATION AND THE RECHARGE
!       IS 1.3424 AT NODE 29. THUS THE ET IS 1.5 - 1.3424 = 0.1576.
!       TO CHECK THIS VALUE BY HAND INFORMATION IS NEEDED FROM THE
!       SIMULATION REGARDING HEAD AND GROUND SURFACE ELEVATION AT NODE 29.

!       THE HEAD AT NODE 29 (PH) IS (AT BEGINNING OF TIME STEP):

PH3  LEVEL 2 SHOW NODE 29

!       THE GROUND SURFACE (GS) IS:

ELEV LEVEL 2 SHOW NODE 29

!       THE EVAPORATION POTENTIAL (EP) AT NODE 29 IS 0.5 (AREA=50. * RATE=.01)
!       THE ACTUAL EVAPORATION SHOULD THEREFORE BE
!          [1-(GS-PH)/DEPTH]*EP = [1-(80-73.152)/10]*0.5
!                               = .1576                  (QED)

END
```

Grid File DFTC12.GRF

```
      33        40

       1         0      10.0
       2         0       5.0
       3         0         0
       4      10.0      10.0
       5      10.0       5.0
       6      10.0         0
       7      20.0      10.0
       8      20.0       5.0
       9      20.0         0
      10      30.0      10.0
      11      30.0       5.0
      12      30.0         0
      13      40.0      10.0
      14      40.0       5.0
      15      40.0         0
      16      50.0      10.0
      17      50.0       5.0
      18      50.0         0
      19      60.0      10.0
      20      60.0       5.0
      21      60.0         0
      22      70.0      10.0
      23      70.0       5.0
      24      70.0         0
      25      80.0      10.0
      26      80.0       5.0
      27      80.0         0
      28      90.0      10.0
      29      90.0       5.0
      30      90.0         0
      31     100.0      10.0
      32     100.0       5.0
      33     100.0         0
```

```
     1        5        4        1                21       20       19       16
     2        2        5        1                22       17       20       16
     3        3        5        2                23       18       20       17
     4        3        6        5                24       18       21       20
     5        8        7        4                25       23       22       19
     6        5        8        4                26       20       23       19
     7        6        8        5                27       21       23       20
     8        6        9        8                28       21       24       23
     9       11       10        7                29       26       25       22
    10        8       11        7                30       23       26       22
    11        9       11        8                31       24       26       23
    12        9       12       11                32       24       27       26
    13       14       13       10                33       29       28       25
    14       11       14       10                34       26       29       25
    15       12       14       11                35       27       29       26
    16       12       15       14                36       27       30       29
    17       17       16       13                37       32       31       28
    18       14       17       13                38       29       32       28
    19       15       17       14                39       30       32       29
    20       15       18       17                40       30       33       32
```

Output File DFTC12.OUT

```
>>>>>  THIS PROGRAM IS THE CONFIDENTIAL AND PROPRIETARY INFORMATION OF      <<<<<
>>>>>  CAMP DRESSER & MCKEE INC.   COPYRIGHT (C) 1990 CAMP DRESSER & MCKEE INC.  <<<<<
>>>>>  AS AN UNPUBLISHED WORK.   ALL RIGHTS RESERVED.                        <<<<<


--- THIS RUN OF DYNFLOW5
--- VERSION 5.18E    (ICCG SOLVER)  SEPT. 1996
--- STARTED AT  1/ 7/98 18:53: 3.
--- ALL OUTPUT WILL BE TAGGED WITH THIS DATE/TIME.


TITL

ENTER THREE TITLE LINES ("!" FOR NO CHANGE) :
TITLE LINE #1 :
TITLE LINE #2 :
TITLE LINE #3 :

HERE IS HOW THE TITLE LINES LOOK --
VERIFICATION CASE NO. 12 -- EVAPORATION AND RECHARGE
STEADY-STATE UNCONFINED ONE-DIMENSIONAL FLOW WITH RECHARGE AND EVAPORATION
RUN BY PVDH, BOULDER CO.


TEXT

        THIS TEST CASE DEMONSTRATES THAT APPROPRIATE
        RECHARGE AND EVAPORATION TERMS ARE ADDED TO THE SOLUTION.

ENDT

! INITIAL MODEL SETUP

GRID READ DFTC12.GRF FORMatted

GRID INFO. NOW BEING PROCESSED ...
```

```
--- GRID DATA NOW BEING CLEARED,
--- PRIOR TO FILE READING.

--- GRID WAS PROCESSED OK.

*** WRITING GRID DATA TO FILE "GRID.SUM"

LEVEL  2.
FREE
ELEM 301.
ELEV   0.      LEVELSING     1
ELEV  80.      LEVELSING     2
INIT  75.
INIT  50.      LEVELALL             NODE RANGE    1    3
FIX            LEVELALL             NODE RANGE    1    3
FIX            LEVELALL             NODE RANGE   31   33
DT     0.
TOL   0001.
ITER   100.

*** SPECIFIED ITERATION LIMIT ..... :   100
*** MUST EXCEED ZERO,
*** BUT NOT THE MAX. ALLOWED ...... :    30
*** CURRENT VALUE RETAINED ........ :     5

!PRAL
NOPR
*** NO DEFAULT PRINT FOR THIS RUN
*** USE "SUMM","ERRO", AND "PRIN" COMMANDS
*** FOR RESULTS AS REQUIRED.

!       THE FIRST CASE SETS THE ELEMENT RECHARGE
!       USING THE ORIGINAL METHOD OF ASSIGNMENT
!       OF RECHARGE THROUGH THE 'PROP' COMMAND.
!       THE GRID AREA IS 1000 FT.SQ. AND THE
!       RECHARGE IS 0.01 FT/D GIVING A TOTAL FLUX
!       OF 10 CFD

PROP

ENTER PROPERTIES IN FOLLOWING ORDER --
#,KXX,KYY,KZZ,STORATIVITY,SPEC. YIELD,RECHARGE,THETA,PHI,SPEC. GRAV.,EFF. STRESS:
1,1.,1.,100.,0.,0.,0.01,0.,0.

GOTIL 0.
 *** I.C.C.G. SOLVER SELECTED

CG  HAS CONVERGED IN     16 ITERATIONS
 TIME:      .00, ITER.:  1, MAX.ERR.:   22.03, AT NODE:    6, LEVEL:  1, TOL.:    1.00

CG  HAS CONVERGED IN     16 ITERATIONS
 TIME:      .00, ITER.:  2, MAX.ERR.:    1.02, AT NODE:   16, LEVEL:  2, TOL.:    1.00

CG  HAS CONVERGED IN     16 ITERATIONS
 TIME:      .00, ITER.:  3, MAX.ERR.:     .04, AT NODE:    7, LEVEL:  2, TOL.:    1.00

!PRIN

!       THE COMPUTED TOTAL RECHARGE SHOWN BELOW SHOULD BE 10 CFD (FIRST LINE).

FLXL LEVEL 2 SUM
 ***
 ***   THE SUM OF THE SPECIFIED VALUES IS:        9.999999
 ***   THE AVERAGE OF THE SPEC. VALUES IS:    3.030303E-01
 ***   THE MAXIMUM OF THE SPEC. VALUES IS:    5.000000E-01
 ***   THE MINIMUM OF THE SPEC. VALUES IS:    8.333334E-02
 ***   THE SUM OF THE POSITIVE  VALUES IS:        9.999999
 ***   THE SUM OF THE NEGATIVE  VALUES IS:    0.000000E+00
 ***
```

```
 !       THE SECOND CASE USES THE 'RECH' COMMAND WITH
 !       THE ELEMENT SPECIFICATION. THIS RECHARGE WILL BE ADDED
 !       TO THE ORIGINAL VALUE GIVEN THROUGH THE 'PROP' COMMAND
 !       TO GIVE A TOTAL OF 20 CFD.

RECH  0.01 ELEM ALL
GOTI  0.
 *** I.C.C.G. SOLVER SELECTED

CG  HAS CONVERGED IN    16 ITERATIONS
 TIME:     .00, ITER.:  1, MAX.ERR.:     .20, AT NODE:   16, LEVEL:  2, TOL.:    1.00

!PRIN

 !       THE COMPUTED TOTAL RECHARGE SHOWN BELOW SHOULD BE 20 CFD (FIRST LINE).

FLXL LEVEL 2 SUM
 ***
 ***  THE SUM OF THE SPECIFIED VALUES IS:      19.999990
 ***  THE AVERAGE OF THE SPEC. VALUES IS:    6.060604E-01
 ***  THE MAXIMUM OF THE SPEC. VALUES IS:    9.999995E-01
 ***  THE MINIMUM OF THE SPEC. VALUES IS:    1.666666E-01
 ***  THE SUM OF THE POSITIVE  VALUES IS:      19.999990
 ***  THE SUM OF THE NEGATIVE  VALUES IS:    0.000000E+00
 ***

 !       THE THIRD CASE USES THE 'RECH' COMMAND WITH
 !       THE NODE SPECIFICATION. THE NUMBER OF NODES IS
 !       33 SO THAT THE TOTAL RECHARGE WILL NOW BE
 !       43 CFD (10 + 33*1.0). NOTE THAT THE 'RECH' COMMAND
 !       REPLACES THE ORIGINAL VALUES SET BY THE 'RECH'
 !       COMMAND BEFORE.

RECH  1.0 NODE ALL
GOTI  0.
 *** I.C.C.G. SOLVER SELECTED

CG  HAS CONVERGED IN    16 ITERATIONS
 TIME:     .00, ITER.:  1, MAX.ERR.:     .40, AT NODE:   16, LEVEL:  2, TOL.:    1.00

!PRIN

 !       THE COMPUTED TOTAL RECHARGE SHOWN BELOW SHOULD BE 43 CFD (FIRST LINE).

FLXL LEVEL 2 SUM
 ***
 ***  THE SUM OF THE SPECIFIED VALUES IS:      43.000000
 ***  THE AVERAGE OF THE SPEC. VALUES IS:       1.303030
 ***  THE MAXIMUM OF THE SPEC. VALUES IS:       1.500000
 ***  THE MINIMUM OF THE SPEC. VALUES IS:       1.083333
 ***  THE SUM OF THE POSITIVE  VALUES IS:      43.000000
 ***  THE SUM OF THE NEGATIVE  VALUES IS:    0.000000E+00
 ***

 !       THE FOURTH CASE USES THE 'EVAP' COMMAND FOR ALL NODES.
 !       TO CHECK ITS OPERATION, THE RECHARGE AT NODE 29 (LOCATED ALONG THE
 !       CENTER AXIS OF THE GRID) WITH NO EVAPORATION SHOULD BE 1.5 CFD.
 !       THE RECHARGE AT NODE 29 WITH EVAPORATION SHOULD BE 1.3424 CFD.

 !       RECHARGE AT NODE 29 WITHOUT EVAPORATION SHOWN BELOW SHOULD EQUAL 1.5 CFD

FLXL LEVEL 2 NODE 29 SHOW
   2,     29,  1.500000     ,  .0000000

EVAP 0.01 DEPTH  10. ELEM ALL
GOTI
 *** I.C.C.G. SOLVER SELECTED
```

```
CG  HAS CONVERGED IN    16 ITERATIONS
 TIME:     .00, ITER.:  1, MAX.ERR.:     .02, AT NODE:   24, LEVEL:  2, TOL.:    1.00

!       RECHARGE AT NODE 29 WITH ET SHOWN BELOW SHOULD BE 1.3424 CFD.

FLXL LEVEL 2 NODE 29 SHOW
   2,    29,  1.342437    ,  .0000000

!       THE ALGEBRAIC SUM OF THE EVAPORATION AND THE RECHARGE
!       IS 1.3424 AT NODE 29. THUS THE ET IS 1.5 - 1.3424 = 0.1576.
!       TO CHECK THIS VALUE BY HAND INFORMATION IS NEEDED FROM THE
!       SIMULATION REGARDING HEAD AND GROUND SURFACE ELEVATION AT NODE 29.

!       THE HEAD AT NODE 29 (PH) IS (AT BEGINNING OF TIME STEP):

PH3  LEVEL 2 SHOW NODE 29
   2,    29,  73.15127    ,  .0000000

!       THE GROUND SURFACE (GS) IS:

ELEV LEVEL 2 SHOW NODE 29
   2,    29,  80.00000    ,  .0000000

!       THE EVAPORATION POTENTIAL (EP) AT NODE 29 IS 0.5 (AREA=50. * RATE=.01)
!       THE ACTUAL EVAPORATION SHOULD THEREFORE BE
!          [1-(GS-PH)/DEPTH]*EP = [1-(80-73.152)/10]*0.5
!                               = .1576                  (QED)

END

--- THIS RUN OF DYNFLOW5
--- VERSION 5.18E    (ICCG SOLVER)  SEPT. 1996
--- WHICH STARTED AT  1/ 7/98 18:53: 3

--- IS ENDING AT      1/ 7/98 18:53: 5
```

Test 14: ANISOTROPY

test #:	DFTC14
command file:	DFTC14.CFI
grid file:	DFTC14.GRF
output file:	DFTC14.OUT
date of test execution:	April 1, 1998
title:	Radial confined transient flow with anisotropy
description:	Transient flow towards a fully penetrating pumping well with a constant discharge rate in an anisotropic, homogeneous, confined porous medium of infinite extent and constant thickness (see figure B14-1 and B14-2).

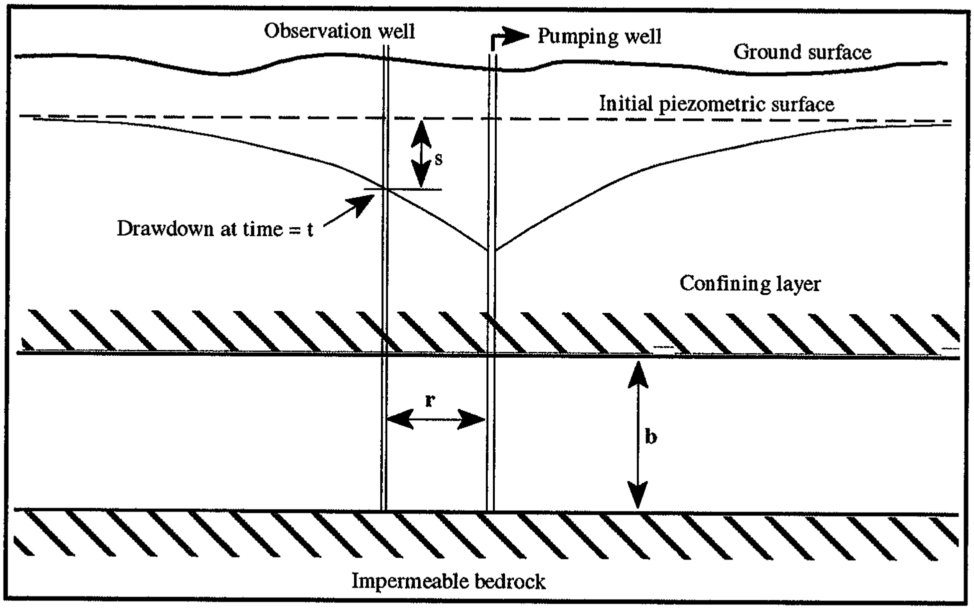

Figure B14-1.

tested functions:	Transient horizontal flow under confined anisotropic conditions; effects of discharging well; influence of lateral fixed head boundary condition.
model domain:	*Analytical solution*: infinite horizontal extent, aquifer thickness b = 10 ft; *numerical model*: 90° segment of radial domain with radius= 12,000 ft.

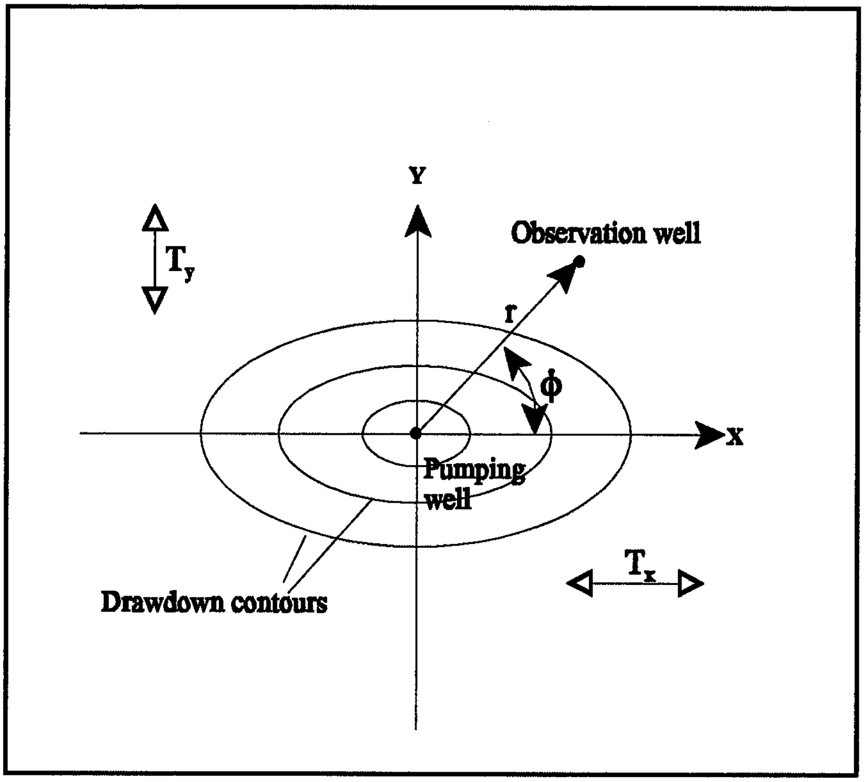

Figure B14-2

boundary conditions: Fixed head at outer radial boundary (R=12,000 ft) is $h_R = 100$ ft; well discharge rate Q = 1000 ft^3/d is distributed as a specified flux boundary condition in the central node; remaining boundary nodes are specified as no-flow boundaries.

benchmark: Hantush-Thomas analytical solution for drawdown with given transmissivities, storativity and pumping rate:

$$s = \frac{Q}{4\pi\sqrt{(T_x T_y)}} W(u)$$

where

$$u = \frac{r^2 S}{4 t T_r}$$

and

$$T_r = \frac{T_x}{\cos^2\phi + \frac{T_x}{T_y}\sin^2\phi}$$

where, $\boldsymbol{Q}$ = flow rate $[L^3/T]$, $\boldsymbol{T_x}$, $\boldsymbol{T_y}$ = transmissivity in x-direction and y-direction, respectively $[L^2/T]$, $\boldsymbol{S}$ = storativity [fraction], $\boldsymbol{r}$ = radial distance from pumping well to observation well [L], $\boldsymbol{t}$ = time since start of pumping [T], $\boldsymbol{s}$ = drawdown in observation well with respect to prepumping horizontal piezometric surface [L], $\boldsymbol{\phi}$ = the angle between the x-axis and the line between the pumping well and the observation well, and $\boldsymbol{W}$ = the Theis Well Function [dimensionless]. Transmissivities are calculated from respective hydraulic conductivities multiplied by aquifer thickness. Calculation are made for observation wells at r = 150, 250, 400, 550, and 900 ft from the well, respectively.

grid: single layer full quadrant (90°) grid with two levels (see Figure B14-3); in plan view, the grid consists of 169 nodes defining 282 elements.

initial conditions: h=100 ft

time-stepping: Model time steps of 0.1 days; comparison at t=1 day.

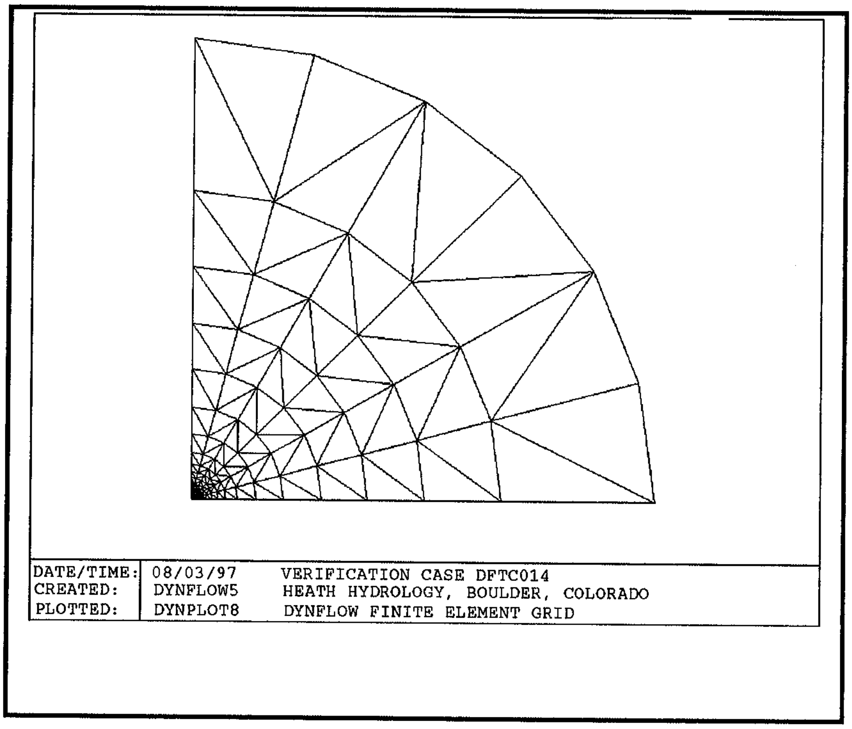

Figure B14-3.

system parameters: hydraulic conductivity k_x = 1000 m/d; K_y = 100 m/d; k_z = 100 ft/d; specific storativity = 0.00001 ft^{-1} (storage coefficient = 0.001); aquifer specific yield = 0.10 (not used).

control parameters: Tolerance = .0001 ft; alpha = 1.5 (relaxation factor); acce = 1.5; max. # outer iterations = 30; max. # inner iterations = 90

solver: ICCG

test performed by: Problem set up for numerical code prepared by code developers; code run and benchmark comparison performed by test report author.

type of comparison: Tabular listing of heads (see Table B14-1); no statistical measures calculated.

Table B14-1.

	Drawdown (ft)									
	r = 150 ft		r = 250 ft		r = 400 ft		r = 550 ft		r = 900 ft	
angle ϕ degrees	BM	DF	BM	DF	BM	DF	BM	DF	BM	DF
0	1.16	1.10 (58)	0.91	0.86 (72)	0.68	0.65 (86)	0.52	0.50 (93)	0.31	0.29(107)
45	0.74	0.72 (61)	0.49	0.49 (75)	0.29	0.29 (89)	0.17	0.18 (96)	0.05	0.05(110)
90	0.59	0.59 (64)	0.36	0.36 (78)	0.18	0.19 (92)	0.09	0.09 (99)	0.01	0.01(113)
BM = Benchmark; DF = Dynflow (node number between brackets)										

# iterations:	27
influx [ft^3/d]:	257.429
outflux [ft^3/d]:	257.464
total mass balance error:	.01 %

performance notes: The computed heads compare very well with the benchmark, both in the direction of the X-axis and in the direction perpendicular to the x-axis.

Command File DFTC14.CFI

```
OUTPUT DFTC14.OUT

TITLE
VERIFICATION CASE NO. 14 -- ANISOTROPY; RUN BY PVDH, BOULDER, CO.
TRANSIENT CONFINED FLOW TOWARDS A FULLY PENETRATING WELL IN AN
ANISOTROPIC AQUIFER TX>TY.

GRID READ DFTC14.GRF FORM

LEVEL  2.
FREE
ELEV   0.      LEVELSING     1
ELEV  10.      LEVELSING     2
PROP
1,100.,10.,100.,0.0001,0.10,0.,0.,0.
ELEM  301.
```

```
INIT  100.
FIX             LEVELALL             NODE RANGE  163  169
FLUX -125.      LEVELALL             NODE SING   1
DT   0.1
TOL  .0001
ACCE 1.5
PRAL
ALPHA 1.5
ITIN  90.
ITER  30.
NOPR
GOTIL 1
PRINT

XCFI
```

Grid File DFTC14.GRF

```
       169       282

         1      .000      .000
         2     4.000      .000
         3     3.864     1.035
         4     3.464     2.000
         5     2.828     2.828
         6     2.000     3.464
         7     1.035     3.864
         8      .000     4.000
         9     10.00      .000
        10     9.659     2.588
        11     8.660     5.000
        12     7.071     7.071
        13     5.000     8.660
        14     2.588     9.659
        15      .000     10.00
        16     18.00      .000
        17     17.39     4.659
        18     15.59     9.000
        19     12.73     12.73
        20     9.000     15.59
        21     4.659     17.39
        22      .000     18.00
        23     30.00      .000
        24     28.98     7.765
        25     25.98     15.00
        26     21.21     21.21
        27     15.00     25.98
        28     7.765     28.98
        29      .000     30.00
        30     45.00      .000
        31     43.47     11.65
        32     38.97     22.50
        33     31.82     31.82
        34     22.50     38.97
        35     11.65     43.47
        36      .000     45.00
        37     65.00      .000
        38     62.79     16.82
        39     56.29     32.50
        40     45.96     45.96
        41     32.50     56.29
        42     16.82     62.79
        43      .000     65.00
        44     90.00      .000
        45     86.93     23.29
        46     77.94     45.00
        47     63.64     63.64
        48     45.00     77.94
        49     23.29     86.93
        50      .000     90.00
        51     120.0      .000
        52     115.9     31.06
        53     103.9     60.00
        54     84.85     84.85
        55     60.00     103.9
        56     31.06     115.9
        57      .000     120.0
        58     150.0      .000
        59     144.9     38.82
        60     129.9     75.00
        61     106.1     106.1
        62     75.00     129.9
        63     38.82     144.9
        64      .000     150.0
        65     200.0      .000
        66     193.2     51.76
        67     173.2     100.0
        68     141.4     141.4
        69    100.00     173.2
        70     51.76     193.2
        71      .000     200.0
        72     250.0      .000
        73     241.5     64.70
        74     216.5     125.0
        75     176.8     176.8
        76     125.0     216.5
        77     64.70     241.5
        78      .000     250.0
        79     325.0      .000
        80     313.9     84.12
        81     281.5     162.5
        82     229.8     229.8
        83     162.5     281.5
        84     84.12     313.9
        85      .000     325.0
        86     400.0      .000
        87     386.4     103.5
        88     346.4     200.0
        89     282.8     282.8
        90     200.0     346.4
        91     103.5     386.4
        92      .000     400.0
```

```
   93      550.0      .000                            134      .000      2400.
   94      531.3     142.4                            135     3400.       .000
   95      476.3     275.0                            136     3284.      880.0
   96      388.9     388.9                            137     2944.      1700.
   97      275.0     476.3                            138     2404.      2404.
   98      142.4     531.3                            139     1700.      2944.
   99       .000     550.0                            140     880.0      3284.
  100      700.0      .000                            141      .000      3400.
  101      676.1     181.2                            142     4600.       .000
  102      606.2     350.0                            143     4443.      1191.
  103      495.0     495.0                            144     3984.      2300.
  104      350.0     606.2                            145     3253.      3253.
  105      181.2     676.1                            146     2300.      3984.
  106       .000     700.0                            147     1191.      4443.
  107      900.0      .000                            148      .000      4600.
  108      869.3     232.9                            149     6100.       .000
  109      779.4     450.0                            150     5892.      1579.
  110      636.4     636.4                            151     5283.      3050.
  111      450.0     779.4                            152     4313.      4313.
  112      232.9     869.3                            153     3050.      5283.
  113       .000     900.0                            154     1579.      5892.
  114      1200.      .000                            155      .000      6100.
  115      1159.     310.6                            156     8100.       .000
  116      1039.     600.0                            157     7824.      2096.
  117      848.5     848.5                            158     7015.      4050.
  118      600.0     1039.                            159     5728.      5728.
  119      310.6     1159.                            160     4050.      7015.
  120       .000     1200.                            161     2096.      7824.
  121      1700.      .000                            162      .001      8100.
  122      1642.     440.0                            163    12100.       .000
  123      1472.     850.0                            164    11688.      3132.
  124      1202.     1202.                            165    10479.      6050.
  125      850.0     1472.                            166     8556.      8556.
  126      440.0     1642.                            167     6050.     10479.
  127       .000     1700.                            168     3132.     11688.
  128      2400.      .000                            169      .001     12100.
  129      2318.     621.2
  130      2078.     1200.
  131      1697.     1697.
  132      1200.     2078.
  133      621.2     2318.

    1        1         2         3                     28       20        21        14
    2        1         3         4                     29       14        22        15
    3        1         4         5                     30       14        21        22
    4        1         5         6                     31       16        23        17
    5        1         6         7                     32       23        24        17
    6        1         7         8                     33       17        25        18
    7        2         9         3                     34       17        24        25
    8        9        10         3                     35       18        25        19
    9        3        11         4                     36       25        26        19
   10        3        10        11                     37       19        27        20
   11        4        11         5                     38       19        26        27
   12       11        12         5                     39       20        27        21
   13        5        13         6                     40       27        28        21
   14        5        12        13                     41       21        29        22
   15        6        13         7                     42       21        28        29
   16       13        14         7                     43       23        30        24
   17        7        15         8                     44       30        31        24
   18        7        14        15                     45       24        32        25
   19        9        16        10                     46       24        31        32
   20       16        17        10                     47       25        32        26
   21       10        18        11                     48       32        33        26
   22       10        17        18                     49       26        34        27
   23       11        18        12                     50       26        33        34
   24       18        19        12                     51       27        34        28
   25       12        20        13                     52       34        35        28
   26       12        19        20                     53       28        36        29
   27       13        20        14                     54       28        35        36
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   55       30       37       31            125      70       78       71
   56       37       38       31            126      70       77       78
   57       31       39       32            127      72       79       73
   58       31       38       39            128      79       80       73
   59       32       39       33            129      73       81       74
   60       39       40       33            130      73       80       81
   61       33       41       34            131      74       81       75
   62       33       40       41            132      81       82       75
   63       34       41       35            133      75       83       76
   64       41       42       35            134      75       82       83
   65       35       43       36            135      76       83       77
   66       35       42       43            136      83       84       77
   67       37       44       38            137      77       85       78
   68       44       45       38            138      77       84       85
   69       38       46       39            139      79       86       80
   70       38       45       46            140      86       87       80
   71       39       46       40            141      80       88       81
   72       46       47       40            142      80       87       88
   73       40       48       41            143      81       88       82
   74       40       47       48            144      88       89       82
   75       41       48       42            145      82       90       83
   76       48       49       42            146      82       89       90
   77       42       50       43            147      83       90       84
   78       42       49       50            148      90       91       84
   79       44       51       45            149      84       92       85
   80       51       52       45            150      84       91       92
   81       45       53       46            151      86       93       87
   82       45       52       53            152      93       94       87
   83       46       53       47            153      87       95       88
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   91       51       58       52            161      91       99       92
   92       58       59       52            162      91       98       99
   93       52       60       53            163      93      100       94
   94       52       59       60            164     100      101       94
   95       53       60       54            165      94      102       95
   96       60       61       54            166      94      101      102
   97       54       62       55            167      95      102       96
   98       54       61       62            168     102      103       96
   99       55       62       56            169      96      104       97
  100       62       63       56            170      96      103      104
  101       56       64       57            171      97      104       98
  102       56       63       64            172     104      105       98
  103       58       65       59            173      98      106       99
  104       65       66       59            174      98      105      106
  105       59       67       60            175     100      107      101
  106       59       66       67            176     107      108      101
  107       60       67       61            177     101      109      102
  108       67       68       61            178     101      108      109
  109       61       69       62            179     102      109      103
  110       61       68       69            180     109      110      103
  111       62       69       63            181     103      111      104
  112       69       70       63            182     103      110      111
  113       63       71       64            183     104      111      105
  114       63       70       71            184     111      112      105
  115       65       72       66            185     105      113      106
  116       72       73       66            186     105      112      113
  117       66       74       67            187     107      114      108
  118       66       73       74            188     114      115      108
  119       67       74       68            189     108      116      109
  120       74       75       68            190     108      115      116
  121       68       76       69            191     109      116      110
  122       68       75       76            192     116      117      110
  123       69       76       70            193     110      118      111
  124       76       77       70            194     110      117      118
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 195      111      118      112
 196      118      119      112
 197      112      120      113
 198      112      119      120
 199      114      121      115
 200      121      122      115
 201      115      123      116
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