science for a changing world

Techniques of Water-Resources Investigations of the United States Geological Survey

Chapter A6

A COUPLED SURFACE-WATER AND GROUND-WATER FLOW MODEL (MODBRANCH) FOR SIMULATION OF STREAM-AQUIFER INTERACTION

By Eric D. Swain and Eliezer J. Wexler

Book 6

MODELING TECHNIQUES

LIST OF VARIABLES—Continued

(Value in parentheses is array dimension; only variables necessary to convert BRANCH to BRANCH' are included)

Variable	Range	Definition
MXTDBC	Package	Maximum number of boundaries in the network.
MXWIND	Package	Maximum number of wind data points input.
NCOL	Global	Maximum number of MODFLOW aquifer columns.
NELAP	Package	Number of elapsed MODFLOW time steps since beginning of simulation.
NLAY	Global	Maximum number of MODFLOW aquifer layers.
NROW	Global	Maximum number of MODFLOW aquifer rows.
NTSAQ	Package	Number of BRANCH time intervals in one MODFLOW time step.
QLSUM (MAXS)	Package	Average leakage rate out of a river segment over one MODFLOW time step.
QPSAV (MAXS)	Package	Value of discharge at end of first BRANCH' time interval in a MODFLOW time step.
QSAV (MAXS)	Package	Value of discharge at beginning of first BRANCH' time interval in a MODFLOW time step.
ZBOT (MAXS)	Package	Elevation of channel bottom.
ZN (MAXS)	Package	Value of stage at end of final BRANCH' time interval in a MODFLOW time step.
ZPL (MAXS)	Package	Value of stage at end of final BRANCH' time interval in a MODFLOW time step for previous trial.
ZPSAV (MAXS)	Package	Value of stage at end of first BRANCH' time interval after beginning of a MODFLOW time step.
ZSAV (MAXS)	Package	Value of stage at beginning of first BRANCH' time interval after beginning of a MODFLOW time step.

SIMULATIONS OF STREAM-AQUIFER INTERACTION

The verification procedure for MODBRANCH was developed with the following criteria to be satisfied: (1) compare results with previously existing models; (2) simulate events that cannot be modeled with existing models; (3) demonstrate the use of special options, drying and rewetting of channels and steady-state simulation; and (4) compare simulation results with field data collected at a site in southern Florida.

SCHEMES FOR COMPARISON

In order to verify the MODBRANCH solution scheme, MODBRANCH results were compared with results from three other solution schemes: (1) the one-dimensional, unsteady, constant cross-section model described by Pinder and Sauer (1971); (2) a simple, four-point implicit scheme for a rectangular channel attached to MODFLOW in the same manner that BRANCH was attached; and (3) the flow-routing Stream package for MODFLOW (Prudic, 1989).

The one-dimensional, unsteady, constant cross-section streamflow model (referred to as the Pinder model) solved the continuity and momentum equations by an explicit finite-difference, staggered-net method. The two-dimensional ground-water flow equation is solved by the iterative, alternating direction implicit technique. The streamflow and ground-water equations are coupled by a leakage equation similar to equation 3a. This coupled model was used to demonstrate the modification of a floodwave because of bank storage (Pinder and Sauer, 1971). Thus, the Pinder model results can be reproduced by MODBRANCH for comparison.

The four-point implicit scheme (referred to as the four-point model) was created by Lewis Delong, Jon Lee, and David Thompson of the USGS as a training supplement in surface-water modeling. It solves the continuity and momentum equations in integral form for a unit width of channel. As in the case of the Pinder model, its use is confined to single rectangular channels of constant width. As a prelude to creating MODBRANCH, the four-point model was coupled with MODFLOW. The same format was used as in MODBRANCH; allocation, data input, formulation, and budget subroutines were created for the four-point model. This coupled four-point model can be used for comparison with MODBRANCH.

The stream module in MODFLOW (Prudic, 1989) can route flow from more than one tributary into a channel, so it is not limited to single channels as are the Pinder and four-point models. However, it is restricted to rectangular cross sections; only routes flow downstream, and backwater effects cannot be simulated. Flows into diversions and forks must be user defined, and the depth in each reach is calculated as steady uniform flow. This makes it comparable to MODBRANCH especially in steady-state simulation.

PROBLEM 1—FLOODWAVE PROPAGATION WITH BANK STORAGE

This verification involves duplicating the results from Pinder and Sauer (1971) with MODBRANCH and the four-point model. The hypothetical aquifer used extends 130,000 ft along the length of the channel and is 1,400 ft across. The hydraulic conductivity of the aquifer is 0.01 ft/s (864 ft/d), and the initial saturated thickness ranges from 220 ft at the upstream boundary to 90 ft at the downstream boundary. The aquifer is surrounded by impermeable boundaries. The stream is a straight channel with a constant width of 100 ft and a slope of 0.001. Initial depth of flow in the stream is 20 ft, and the initial discharge is 18,000 ft^3/s.

The suggested *K'/b'* value of 4 ft/s per foot was supposed to be high enough so that riverbed conductance was not a limiting factor in the amount of water entering the aquifer (Pinder and Sauer, 1971). However, a value of 0.01 ft/s per foot would be equivalent to the hydraulic conductivity of the aquifer with a riverbed thickness of 1 ft. This value was used in the trial run, and results indicate the model is not sensitive to higher values. Assuming the 18,000 ft^3/s was normal flow in the channel at a 20-ft depth, Manning's equation indicates an n value of 0.03858. The aquifer storativity was set to a nominal value of 0.25.

With these input data, the stream-aquifer system was modeled on MODBRANCH and the four-point model. The aquifer was defined with a land-surface elevation 1,000 ft above the aquifer base everywhere except at the river, where the aquifer top is defined at the river bottom, effectively making the aquifer confined under the river. The finite-difference grid was arranged with 2,000-ft spacings from north to south (corresponding to the lengths of the river reaches crossing the model grid cell) and 100-ft spacings everywhere from east to west, except on either side of the river where 50-ft spacings were used for detail. The river was continued 10,000 ft beyond the southern boundary of the aquifer (total river length 140,000 ft), and the downstream end was set as a "self-setting boundary condition." This approximates a free outflow.

Because the four-point model is fully forward weighted in time, the weighting factors Θ and χ in BRANCH' were set to one. Because of potential numerical instabilities with a relatively high leakage coefficient, the same time-step and time-interval length of 5 minutes was used in MODFLOW and BRANCH'. Although the exact upstream hydrograph used in Pinder and Sauer (1971) was unknown, a cosine wave was set up with a peak of 28,000 ft^3/s and a length of 2.5 hours.

The discharge hydrographs simulated by BRANCH' (MODBRANCH model) (solid lines) and the four-point model (dotted line) are shown in figure 12. Hydrographs are shown at three points: the upstream boundary, 50,000 ft downstream, and 140,000 ft downstream (10,000 ft beyond the end of the aquifer). The very close correlation in the results of the two models indicates that MODBRANCH has the same solution as the simple four-point scheme coupled to MODFLOW. The modification of the floodwave by leakage can be seen in figure 12 as the downstream hydrographs demonstrate marked attenuation in wave magnitude.

For comparison of MODBRANCH results with results from the Pinder model, discharge hydrographs in the report by Pinder and Sauer (1971) were compared to hydrographs simulated by MODBRANCH (fig. 13). The upper set of curves in figure 13 is the discharge at 50,000 ft from the upstream boundary without leakage; the lower set of curves is at the same location with leakage to the aquifer. The close correlation indicates the MODBRANCH solution corresponds to results from the Pinder model. Small differences between the curves produced by the two models can be attributed to digitizing errors, differing convergence criteria, and differing input hydrographs.

The comparison involving the results from Pinder and Sauer (1971) indicates that MODBRANCH reproduces the results from the four-point and Pinder models for a simple case. This case only involved a single channel with a constant, rectangular cross section. Unlike the four-point and Pinder models, MODBRANCH can simulate channels with nonrectangular, nonprismatic cross sections and complex junctions.

PROBLEM 2—STEADY-STATE SIMULATION, BACKWATER, AND DISTRIBUTION OF FLOWS AT JUNCTIONS

This problem illustrates the steady-state option in MODBRANCH and allows a comparison of MODBRANCH results with results from the Stream package of MODFLOW. It also allows a demonstration of the ability of MODBRANCH to redistribute flows in BRANCH' at junctions based on backwater effects.

The hypothetical aquifer stretches 20,500 ft from north to south and 10,500 ft from east to west and is surrounded by impermeable boundaries. The aquifer is 8 ft thick and has a hydraulic conductivity of 0.28 ft/s (24,000 ft/d). This high conductivity is similar to some values found in southern Florida. The aquifer, being very shallow, will be dominated by the river leakage. The river starts at the center of the northern boundary and proceeds southward 15,250 ft until it divides into two secondary channels that proceed diagonally to the southern boundary (fig. 14). To duplicate the problem on the Stream package, the channels were made rectangular with the main channel 10 ft wide and the secondary channels 7 ft wide. The river has a bottom elevation 4.95 ft above the aquifer bottom at the northern boundary. The main channel has a slope of 0.0001, and the secondary channels each have a slope of 0.000141. The southern river boundaries have bottom elevations 2.375 ft above the aquifer bottom. Manning's n is 0.0145 for all channels, and the flow at the upstream boundary is 50 ft^3/s. The leakage coefficient for the river is 0.0001 per second.

The recharge package in MODFLOW is used to simulate two situations where recharge from precipitation enters the ground water, leaks into the river, and flows out of the area. In the first situation, uniform recharge of 2 ft/yr (0.005472 ft/d) covers the entire area. The second situation is one in which the area has been covered with impermeable material except for a 5,000 by 5,000-ft area in the southwest

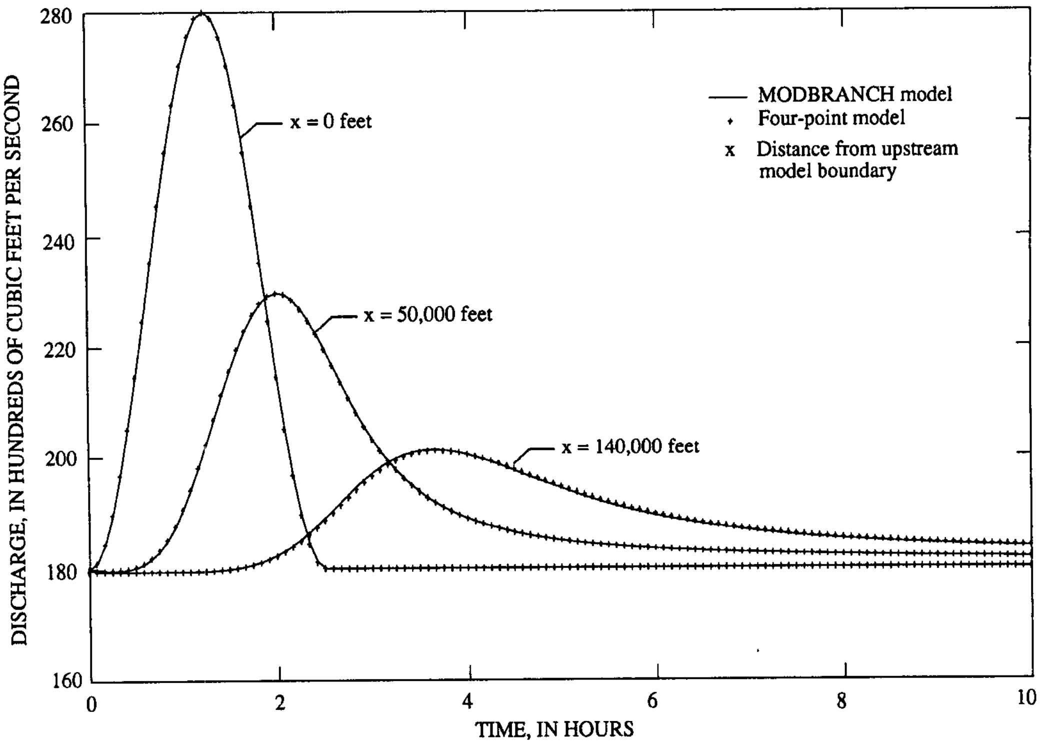

Figure 12. Discharge hydrograph simulated by the MODBRANCH and four-point models.

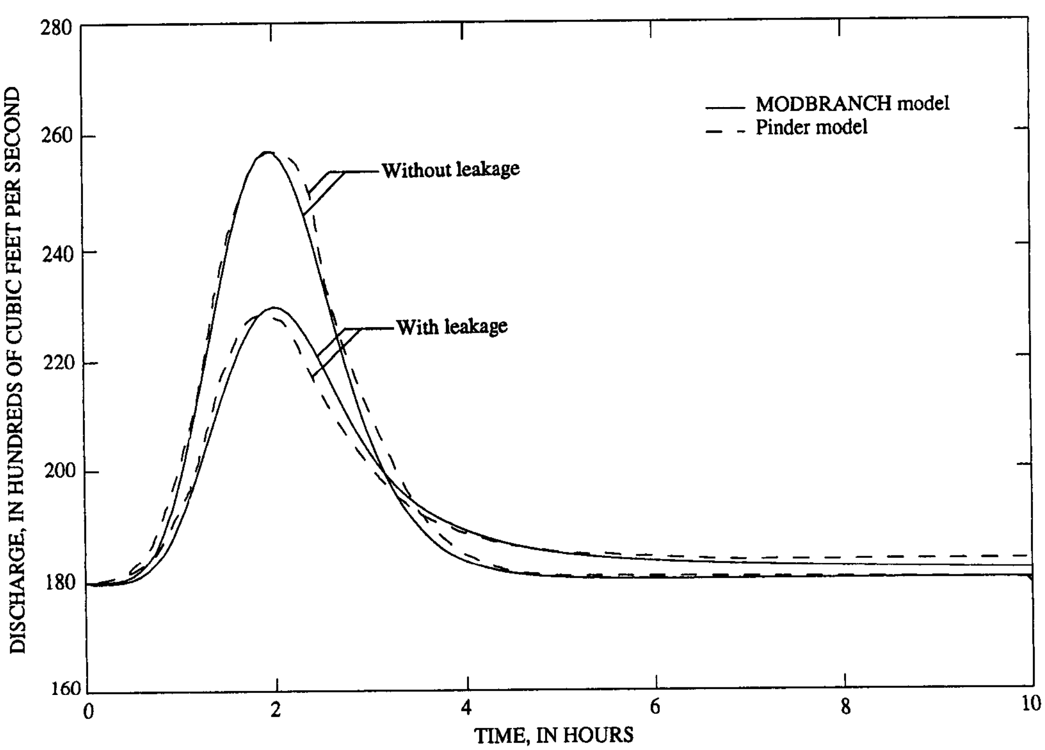

Figure 13. Discharge hydrograph simulated by the MODBRANCH and Pinder models for a site 50,000 feet from upstream boundary.

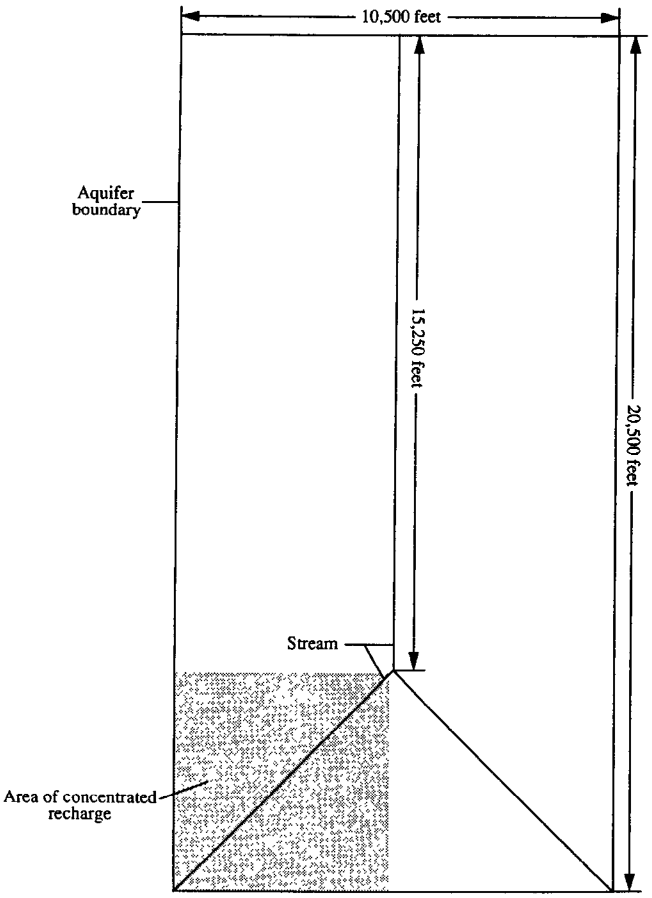

Figure 14. Diagram showing aquifer and river layout for steady-state problem.

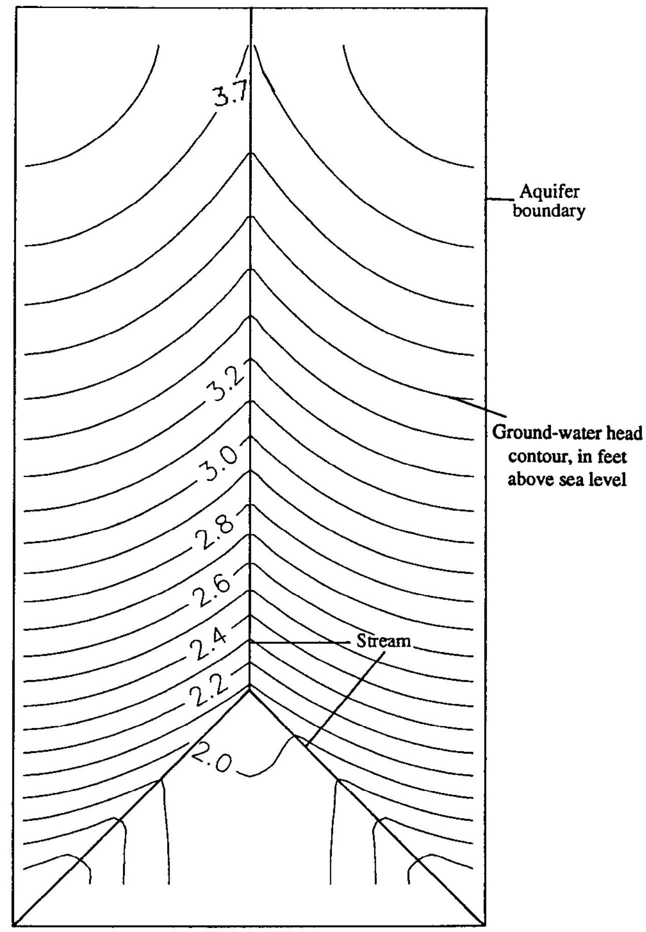

Figure 15. Ground-water head contours produced by MODBRANCH for symmetric recharge (contour interval 0.1 foot).

corner (fig. 14). If the 2 ft/yr recharge over the entire 10,000 by 20,000-ft area was drained into this 5,000 by 5,000-ft area, it would effectively be 16 ft/yr (0.04392 ft/d) in this small area. Taking into account other routes of escape (evaporation and additional drainage areas), a value of 8 ft/yr (0.022536 ft/d) was used in the southwest corner.

A MODFLOW grid spacing of 500 ft was used. The river reaches in BRANCH' and the Stream package were designed to make one reach per aquifer model cell. This made the reaches 500 ft long in the main channel and about 700 ft long in the diagonal secondary channels. In BRANCH', the weighting factors Θ and χ were set to 1 (appropriate for steady state), and the southern boundaries were made "self setting" to simulate free outflows. In the Stream package, the amount of flows going down each secondary channel must be user specified. They were set to divide the flow 50 percent down each channel.

The ground-water contours for the first situation of uniform recharge are shown for MODBRANCH in figure 15 and for the Stream package in figure 16. The close correlation of these two results indicates that backwater conditions in the channel (which can be modeled by MODBRANCH but not by the Stream package) are not greatly affecting the ground-water contours. The river flows produced by the two models are presented in more detail in table 2, which presents stage and discharge at four points along the channel. The two models calculate very similar results with a deviation at the west downstream boundary of only 0.01 ft for stage and 0.1 ft^3/s for discharge.

The ground-water head contours for the second situation of nonuniform recharge are shown for MODBRANCH in figure 17 and for the Stream package in figure 18. The results deviate the most between the two models at the southwest corner. Comparison of figures 17 and 18 shows that MODBRANCH represents the westernmost ground-water mound as farther south, nearer the canal, and having a higher elevation (2.80 ft) than the MODFLOW simulation using the Stream package (2.30 ft). The asymmetrical recharge of the river conditions are apparent from the data presented in the last four columns of table 2.

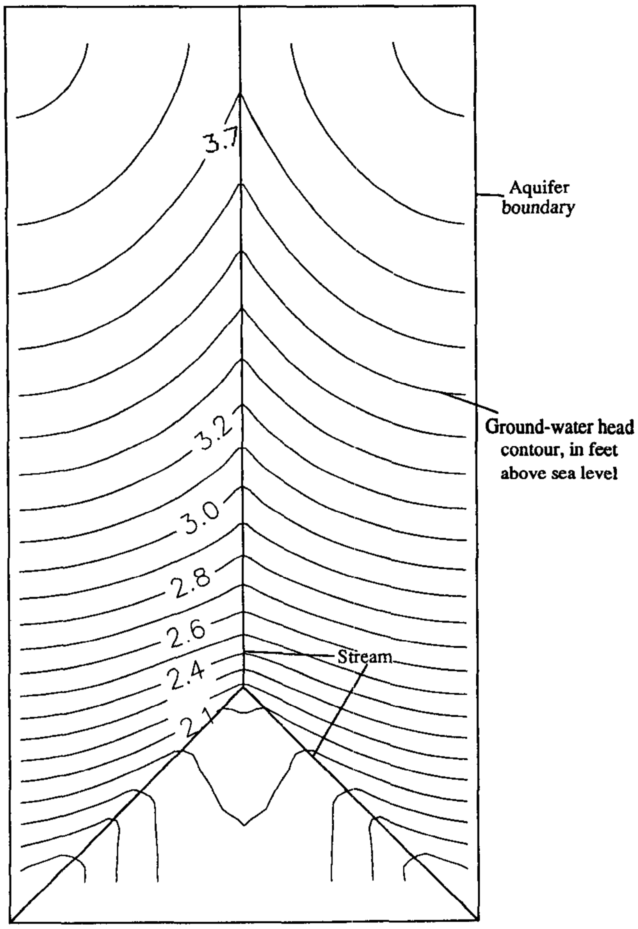

Figure 16. Ground-water head contours produced by stream package for symmetric recharge (contour interval 0.1 foot).

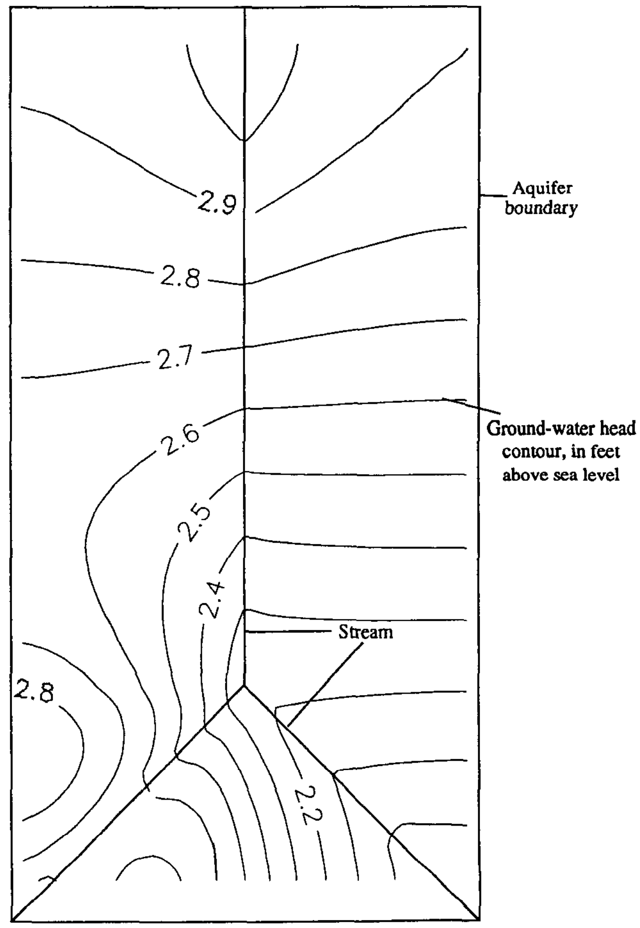

Figure 17. Ground-water head contours produced by MODBRANCH for asymmetric recharge (contour interval 0.1 foot).

Both packages represent virtually the same stage and discharge at the upstream boundary. Immediately upstream of the junction, the BRANCH' stage is 0.50 ft higher than that calculated by the Stream package in MODFLOW. This is primarily because of backwater effects in BRANCH'. Immediately downstream of the junction in the west channel, the Stream package indicates 24.2 ft^3/s, 50 percent of the flow in the main channel; BRANCH' shows 24.1 ft^3/s, 48 percent of the flow in the main channel. Although the percentage of discharge into the west channel is only affected slightly by the backwater effects represented in BRANCH', the stages react more severely. At the downstream boundary, the difference in stages is 0.97 ft. This higher stage, calculated by BRANCH', explains the ground-water mound being higher and closer to the canal in the simulation with MODBRANCH.

These results indicate that MODBRANCH simulates steady-state conditions reasonably well. MODBRANCH differs from the Stream package in MODFLOW in its representation of nonuniform flow and distribution of flows at junctions. These differences can result in significant differences under some conditions.

PROBLEM 3—REWETTING OF CHANNEL BY RECHARGE WELLS

This problem describes a MODBRANCH simulation of a river rewet by discharge from an aquifer. The same aquifer in problem 2 is used with the storativity set to 0.30. A different stream is used, with two tributaries starting from each corner of the northern boundary and joining 5,250 ft south of the northern boundary (fig. 19). A main channel connects the junction to the southern boundary. All channels are rectangular; the tributaries are 10 ft wide, and the main channel is 20 ft wide. All channels have a slope of 0.0001 and a Manning's *n* of 0.0145. The upstream boundaries of the tributaries have riverbed elevations 5.17 ft above the aquifer bottom. At the junction, the riverbed is 4.425 ft above the aquifer bed, and at the southern boundary

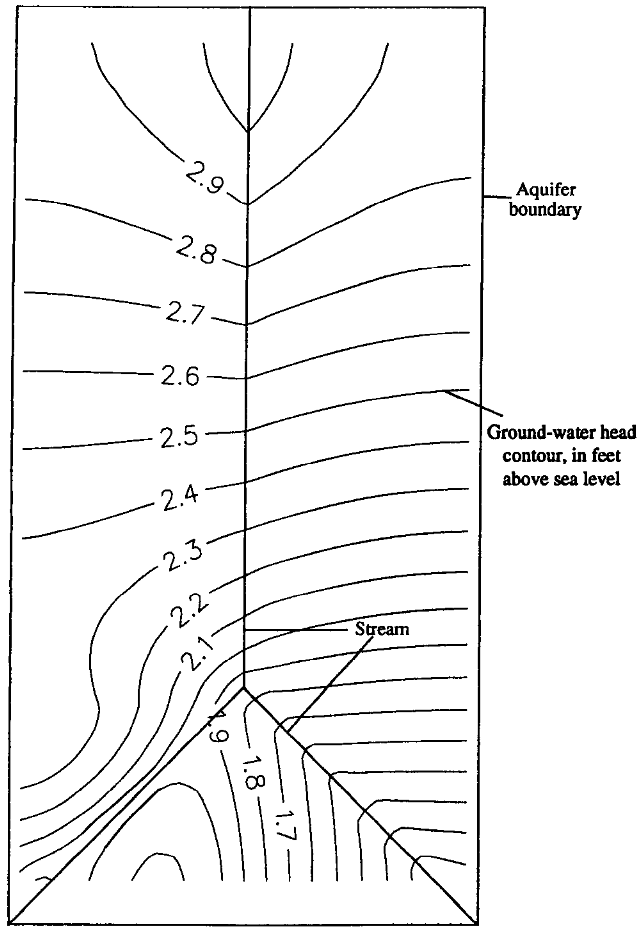

Figure 18. Ground-water head contours produced by stream package for asymmetric recharge (contour interval 0.1 foot).

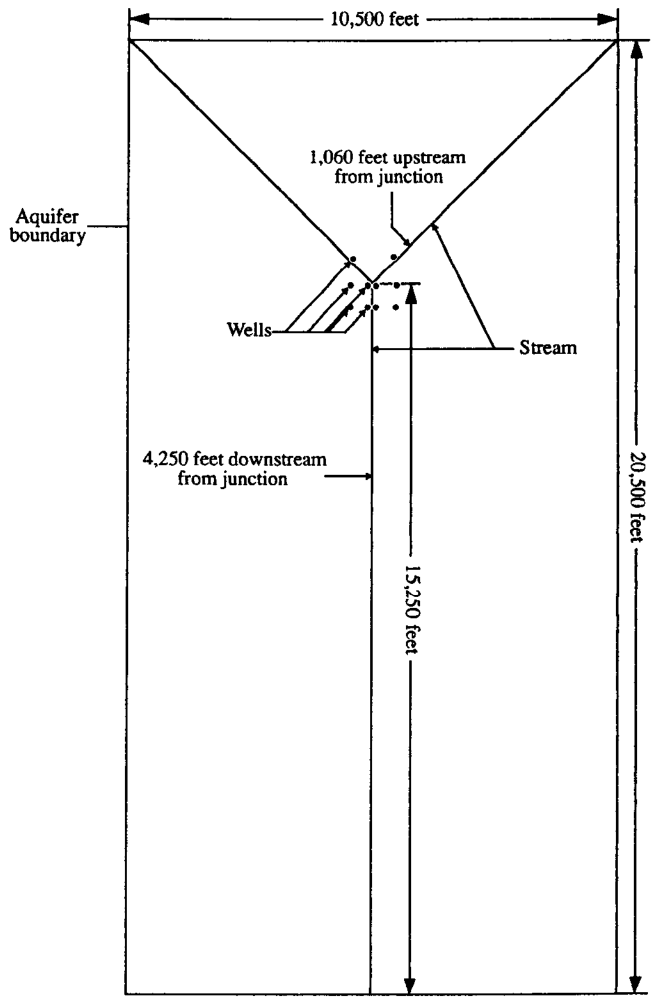

Figure 19. Diagram showing aquifer, river, and well layout for drying and rewetting problem.

it is 2.900 ft above the bed. The leakage coefficient for the river is 0.0010 per second. Grouped around the river junction are 10 recharge wells shown as dots in figure 19. When activated, each well pumps about 11 ft^3/s (40,000 ft^3/hr) into the aquifer.

The simulation starts with the ground-water head 5.0 ft above the aquifer bottom at the northern boundary and sloping linearly to 1 ft above the bottom at the southern boundary (ground-water slope 0.0002). The initial discharge is 15 ft^3/s flowing down each of the tributaries. In the first 45

Table 2. Flows calculated in BRANCH' and stream package of MODFLOW for symmetrical and asymmetrical recharge

[Stage, in feet above or below sea level; discharge, in cubic feet per second]

Location	Symmetrical recharge				Asymmetrical recharge			
	BRANCH'		Stream package		BRANCH'		Stream package	
	Stage	Discharge	Stage	Discharge	Stage	Discharge	Stage	Discharge
Upstream boundary	3.51	50.0	3.49	50.0	3.50	50.0	3.49	50.0
Immediate upstream of junction	1.56	56.3	1.52	55.6	1.85	50.0	1.35	48.3
Immediately downstream of junction in west channel	1.56	28.2	1.47	27.8	1.85	24.1	1.31	24.2
Downstream boundary of west channel	.66	31.5	.67	31.4	1.53	28.0	.56	28.9

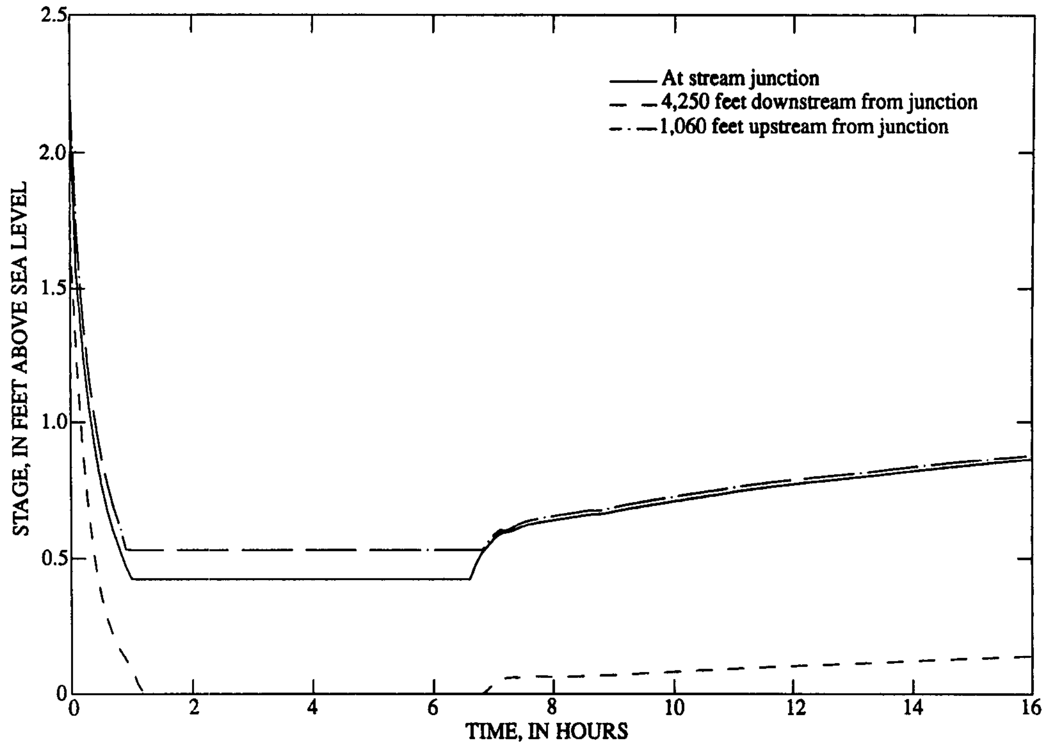

Figure 20. Stage hydrographs for drying and rewetting problem.

minutes, the inflow is cut to zero. The river runs dry. At 4 hours, the 10 wells begin pumping, the aquifer heads around the wells rise until flow from the aquifer fills the channel, rewets it, and flows downstream.

Experimentation indicates a good value for the dry-channel friction multiplier (DCFM) to be 100. Higher values caused small jumps and oscillations in the solution. The time intervals and time steps selected for this run are 6 minutes for BRANCH' and 1 hour for MODFLOW. This allows the option for multiple BRANCH' time intervals in one MODFLOW time step to be demonstrated. The southern boundary of the river is specified as a self-setting boundary condition.

Stage hydrographs at three points in the river are shown in figure 20. The solid line is at the junction, the dashed line is at 4,250 ft downstream, and the dashed-dotted line is 1,060 ft upstream of the junction (points shown in fig. 19). The channel runs dry upstream, at the junction, and downstream. Although the wells start pumping at 4 hours, the ground-water heads do not rise high enough to rewet the channel until about 7 hours. The point at the junction is rewet first with the upstream point not rewet until the stage at the junction has almost reached the bottom elevation of the upstream point. Relatively smooth transitions from wet to dry and dry to wet are indicated. The MODBRANCH output data (Appendix II) indicate that flows of 1–3 ft^3/s occur when the channel is dry. Higher values are present immediately before and after transitions between wet and dry. When rewet, flows of 30–50 ft^3/s are indicated.

The ground-water head contours in the simulation at 6, 10, and 16 hours are shown in figure 21. At 6 hours, the ground-water mound created by the recharge wells becomes apparent, but leakage to the river has not yet begun. At 10 hours, the mound is starting to show a division in the middle because of leakage to the river. By 16 hours, the divide in the ground-water mound is apparent. Finally, figure 22 shows the ground-water head contours at 16 hours if the river is completely removed, but the well recharging schedule is maintained.

To determine the sensitivity of the drying and rewetting option to time-interval length (see Drying and Rewetting of River Channels section), the problem was run again with BRANCH' time intervals of 3 and 12 minutes. A comparison of the hydrographs when time intervals of 3, 6, and 12 minutes are used is shown at the junction, 4,250 ft downstream of the junction, and 1,060 ft upstream of the junction (figs. 23–25). Slight differences occur only at or near the times of drying and rewetting. The solutions are virtually identical at other times. The longer time-interval sizes tend to slightly delay the times of drying and rewetting.

This sample problem demonstrates the ability of MODBRANCH to model a situation where a river runs dry and is rewet from the aquifer by recharging the aquifer with injection wells. It also demonstrates the option of multiple BRANCH' time intervals occurring in one MODFLOW time step. Trial runs indicated that the drying and rewetting process is insensitive to time-interval length in problem 3.

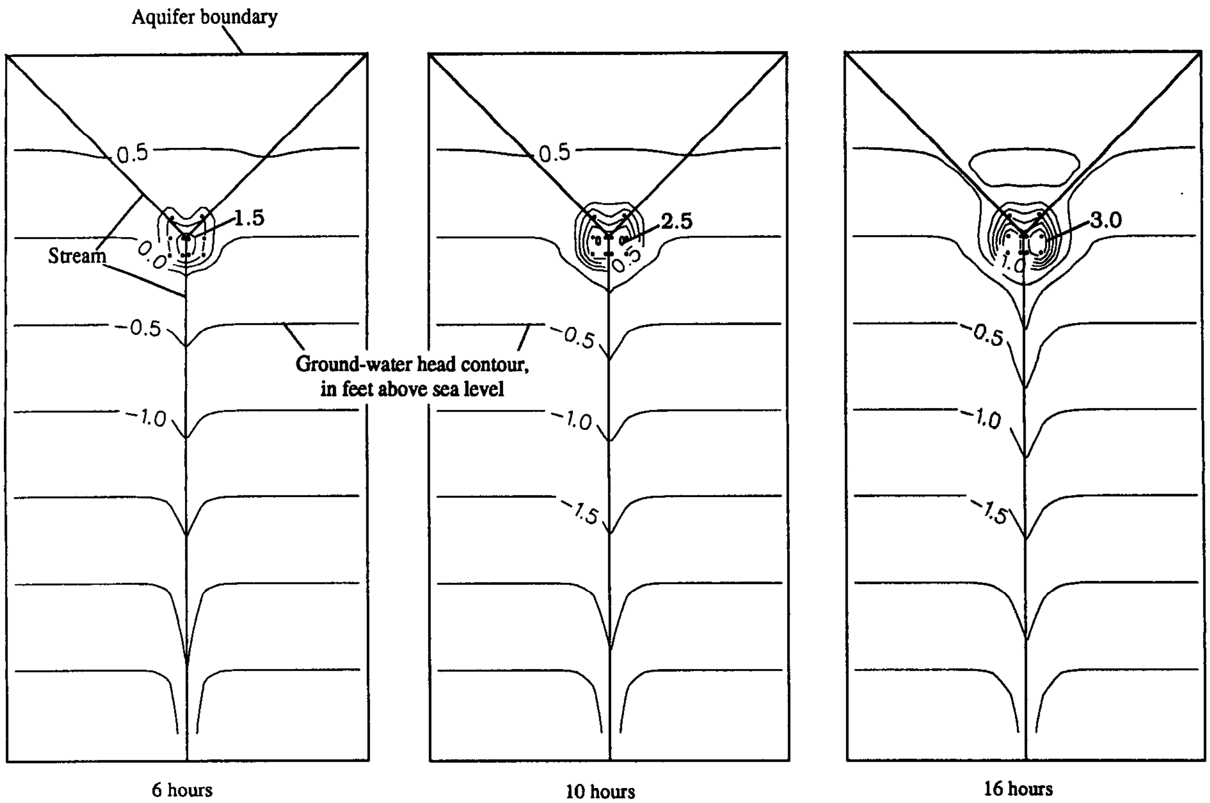

Figure 21. Ground-water head contours at 6, 10, and 16 hours (contour interval 0.5 foot).

PROBLEM 4—FIELD MODEL OF L–31N CANAL

L–31N canal in Dade County (fig. 26) was the site of extensive data collection for a USGS study (Chin, 1990). Three sites along a 2-mi reach beginning at 1 mi south of Tamiami Trail were instrumented with ground-water level measuring wells, stage recorders, and ultrasonic velocity meters (UVM) to measure discharge. The field installation locations are shown in figure 27. The channel cross sections at these three sites were surveyed carefully. The data collected were sufficient to construct a MODBRANCH model of the 2-mi reach of the canal and the surrounding aquifer.

The model aquifer grid for MODFLOW is shown in figure 28. The grid spacings are chosen to place the monitoring wells at the center of grid cells. The aquifer is modeled as one layer with a hydraulic conductivity of 1,667 ft/hr (40,000 ft/d)—a nominal value for the aquifer in this area (Fish and Stewart, 1991). The aquifer top elevation is defined as 8 ft above sea level everywhere, except beneath the canal where the aquifer top elevation is set to the canal-bed elevations, effectively making the aquifer confined beneath the canal. Values of confined storage coefficient and specific yield were chosen, 0.0002 and 0.20, respectively, based on accepted values (M.L. Merritt, U.S. Geological Survey, written commun., 1991). The aquifer bottom elevation is 52.0 ft below sea level.

The time-variant head package for MODFLOW (Leake and Prudic, 1988) was used so that the ground-water heads at the model boundary could be varied during the simulation to match the values recorded in the field. This package allows the ground-water boundary heads to vary linearly from the beginning to the end of a stress period. The simulation included two stress periods, 12 and 48 hours. Each stress period corresponds to a period of comprehensive ground-water data collection.

The channel cross-section measurements were used to define the stage-area-topwidth relations used in BRANCH. Cross sections between the measured locations were defined by interpolating the values of stage, area, and topwidth. The 2-mi canal reach was divided into two branches, each 1 mi long and containing five cross sections. Manning's n value for this type of channel, straight with minimal aquatic growth, was 0.025 (Roberson and others, 1988). For L–31N canal, Chin (1990) concluded that the local reach transmissivity was 630 ft^3/s per mile of canal length per foot of head difference between the canal stage and aquifer head (0.1193 ft^3/s per foot per foot). The local reach transmissivity must be divided by the wetted perimeter to convert to a leakage coefficient, K'/b'. If the average wetted perimeter of L–31N canal is about 135 ft, the value of K'/b' is 0.0009 per second (the value used in BRANCH).

A 15-minute time interval was used in BRANCH and a 4-hour time step was used in MODFLOW. The stage values

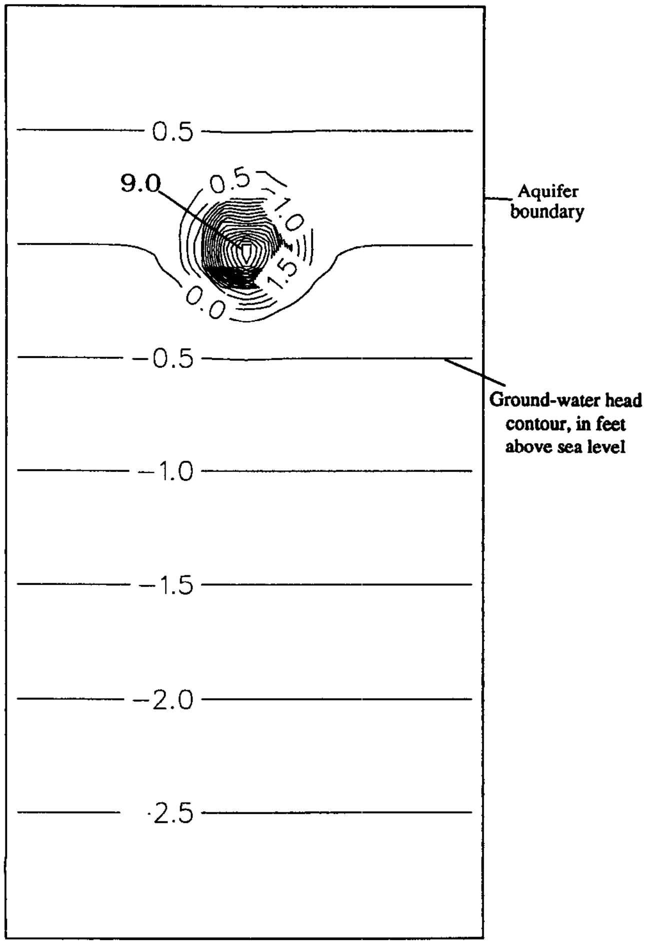

Figure 22. Ground-water head contours at 16 hours without river (contour interval 0.5 foot).

at the upstream and downstream ends of the canal were recorded at 15-minute intervals and were used as boundaries for streamflow routing using the BRANCH' model. The simulation was run from 9:00 p.m. on May 1, 1989, to 9:00 a.m. on May 4, 1989. Verification tests were made by comparing the (1) computed stage at the middle of the channel reach (1 mi from upstream boundary) with measured values, (2) computed discharge at the middle of the channel reach with measured values, and (3) computed ground-water heads with those measured at the interior (not boundary) wells.

RESULTS

The stage computed at the middle of the channel reach is compared to the measured stage at this location in figure 29. The computed stage tends to be slightly higher than the measured stage (0.01 ft or less). This difference is within the order of the accuracy of the stage measurements and these results are considered good. However, because measured stages are used as upstream and downstream boundaries and this comparison point is only 1 mi from each boundary, the closeness of fit can be attributed greatly to boundary effects.

A more rigorous test is to compare computed to measured discharge at the middle of the reach as shown in figure 30. In addition to the initial condition, only two discharge measurements were made using the UVM during the simulation period. The first discharge measurement deviates from the computed value by 76.8 ft^3/s (11.2 percent) because a peak in the model occurs at the time of measurement. However, if the actual time of measurement had been 8:15 a.m. on May 2, 1989, 30 minutes before the time written in the field notes, the deviation would be 10.2 ft^3/s (1.5 percent error). Because of the time for setup of the UVM, the recorded time of measurement could be in error. The second discharge measurement deviates by 6.1 ft^3/s (0.9 percent error). Thus, based on the sparse discharge-measurement data, the model seems to represent the flow in the canal reasonably well without any calibration effort. The model results and the field measurements (Chin, 1990) indicate that the leakage loss along the 2-mi reach during this period could be more than 100 ft^3/s Thus, simulating the canal leakage to the aquifer is critical to model accuracy.

Water-level measurements in observation wells and UVM discharge measurements in the L–31N canal were made simultaneously. The only wells not on the aquifer boundaries are those at sites 4, 5, and 6 (fig. 27). These data are presented along with model results at 9:00 a.m. on May 2, 1989, and 9:00 a.m. on May 4, 1989, in table 3. The shallowest well at each site was used for comparison because the depths of these wells were similar to the depth of the canal. Head differences between the measured and simulated heads varied from 0.01 to 0.07 ft (table 3). Inspection of the field data at these locations (Chin, 1990) indicates that vertical head variation at each site varied from 0.0 to 0.07 ft at the times of measurement. Therefore, the difference between the model and field results can be largely attributable to modeling the aquifer as a single layer. It is also likely that a calibration effort could produce even closer results, but the noncalibrated results shown in figures 29 and 30 are considered a better test of model validity.

CONCLUSIONS

The U.S. Geological Survey models, MODFLOW and BRANCH, were coupled with an interfacing code called MODBRANCH to allow the simulation of ground-water and surface-water interactions with sophisticated models of both systems. The BRANCH code was modified to implement this connection. The modified BRANCH code, referred to as BRANCH', was designed to operate from a subroutine package in MODFLOW. This configuration allows multiple BRANCH' time intervals to pass during one

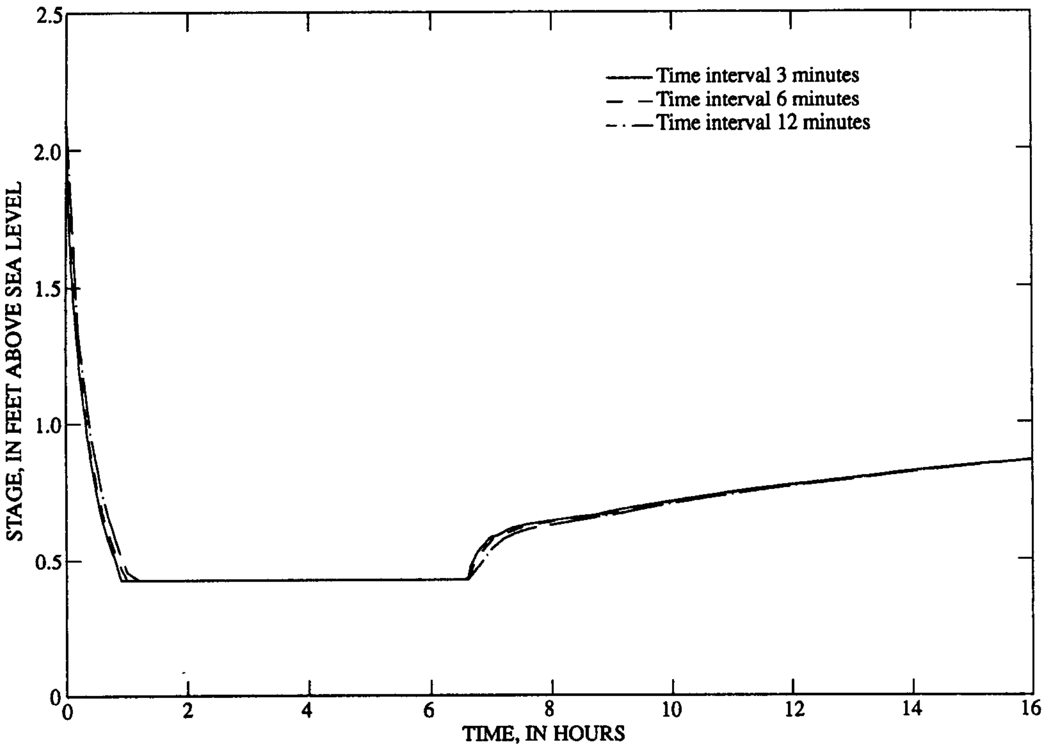

Figure 23. Stage hydrograph for time intervals of 3, 6, and 12 minutes at a site at the stream junction.

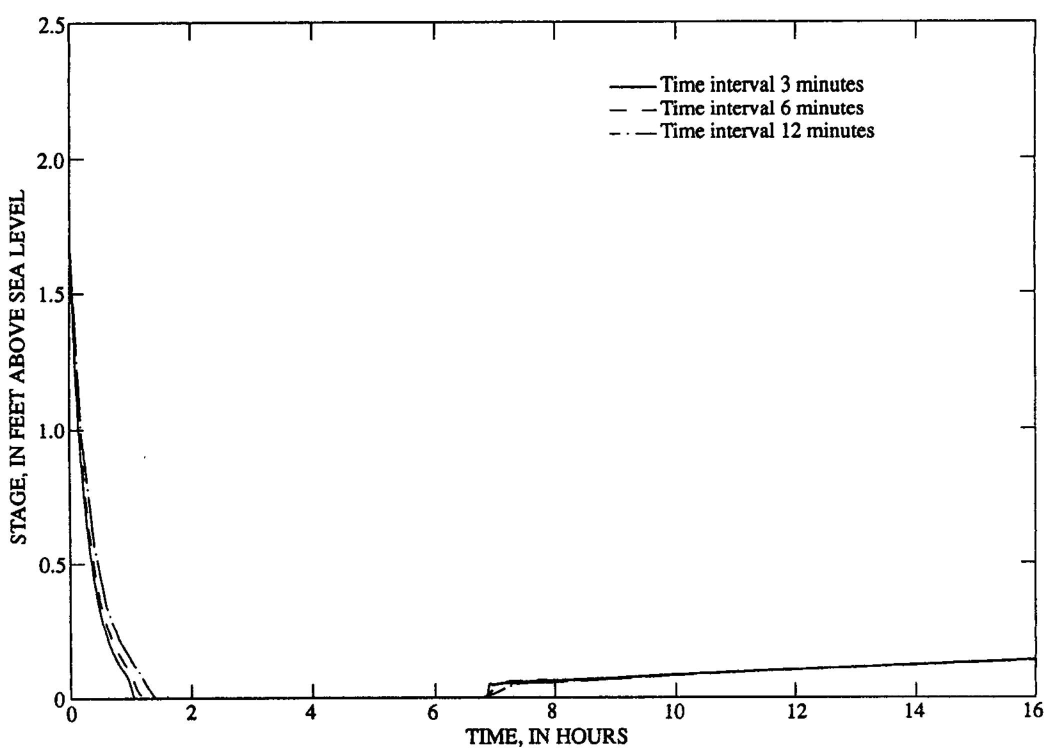

Figure 24. Stage hydrograph for time intervals of 3, 6, and 12 minutes at a site 4,250 feet downstream from the stream junction.

Table 3. Measured and model computed ground-water levels at the L–31N canal test site

Date	Time	Well	Measured water level (feet above sea level)	Computed water level (feet above sea levels)	Difference (feet)
5/2/89	9:00 a.m.	4	4.63	4.70	0.07
		5	4.65	4.68	.03
		6	4.63	4.66	.03
5/4/89	9:00 a.m.	4	4.53	4.58	.05
		5	4.54	4.55	.01
		6	4.50	4.53	.03

MODFLOW time step. When the time-step and time-interval lengths are the same in MODFLOW and BRANCH', the leakage quantities are calculated separately in MODFLOW and BRANCH'. This is the most stable scheme numerically. However, when multiple BRANCH' time intervals occur within one MODFLOW time step, the leakage values calculated in BRANCH' are passed to MODFLOW. This is necessary to conserve proper mass balance.

Additional features of the coupled model are the modularization of BRANCH' to allow its arrays to be passed from main arrays in MODFLOW, an option to allow the channel to dry and rewet, and a steady-state option that reduces the equations in BRANCH' to their nontime-dependent form if MODFLOW is running with the steady-state option. Sample runs have shown the usefulness of these options as well as the validity of MODBRANCH's formulation by comparison to previous models and to field data collected at a test site on the L–31N canal in southern Florida.

The new coupled model using the MODBRANCH code is most applicable when rapid stream and aquifer changes are modeled in a well-connected system. It can be used in conjunction with the simpler River and Stream packages with BRANCH' applied specifically to the transient, multiple junctioned, or irregular cross-sectioned rivers.

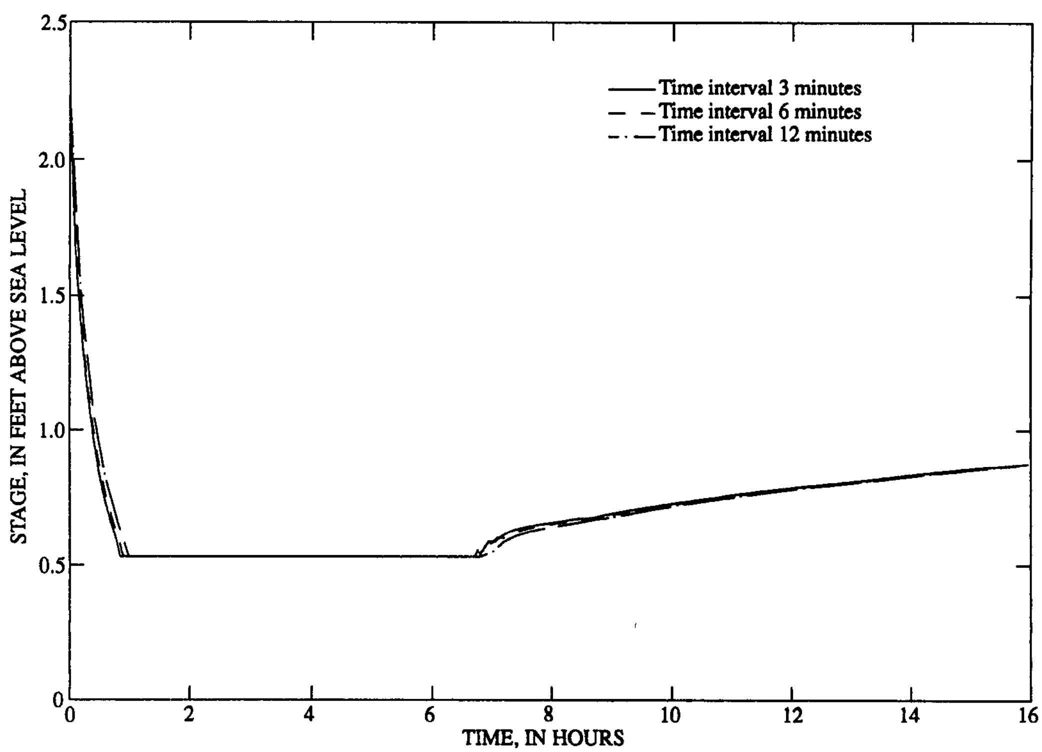

Figure 25. Stage hydrograph for time intervals of 3, 6, and 12 minutes at a site 1,060 feet upstream from the stream junction.

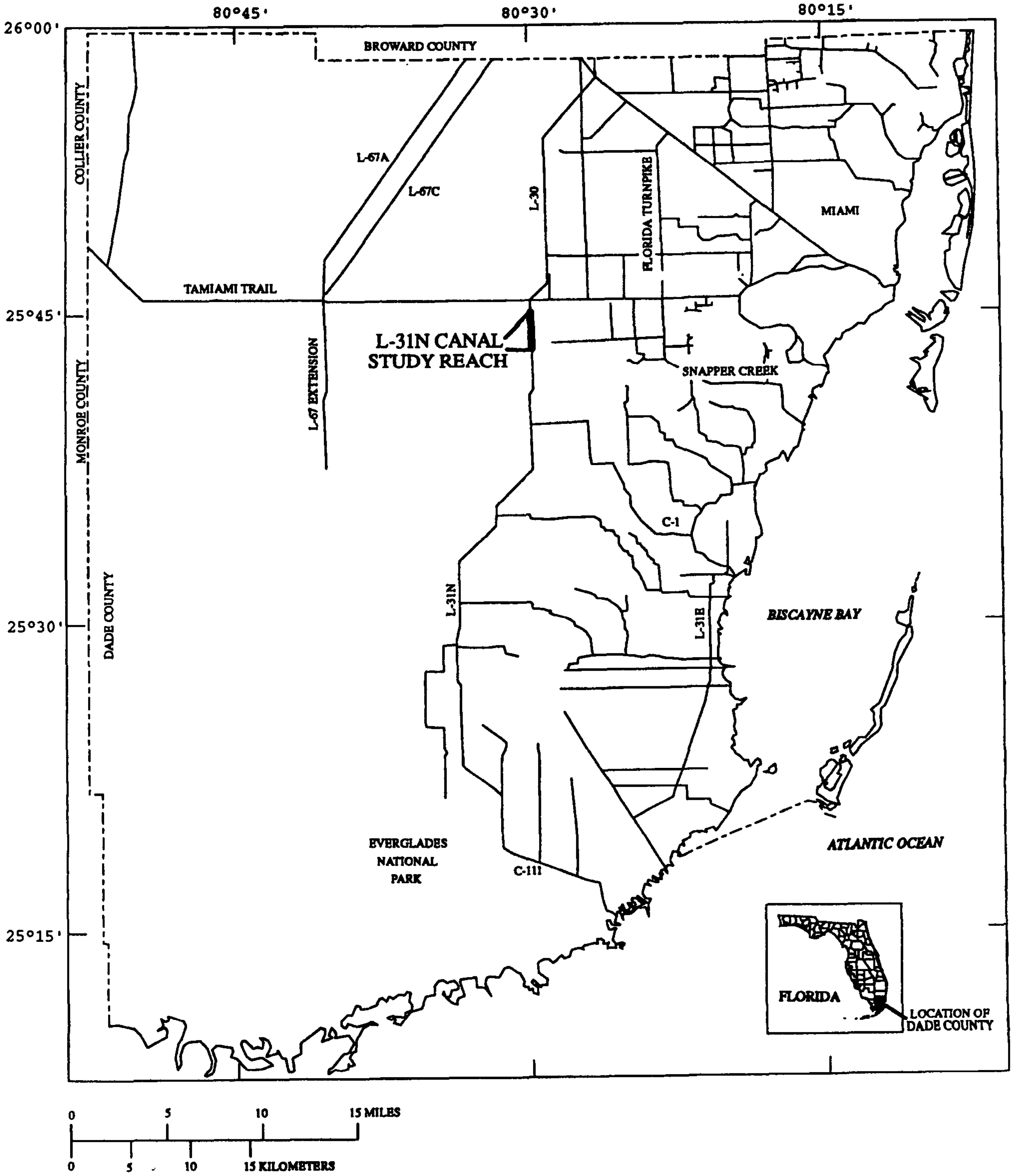

Figure 26. Map showing location of L–31N canal test reach.

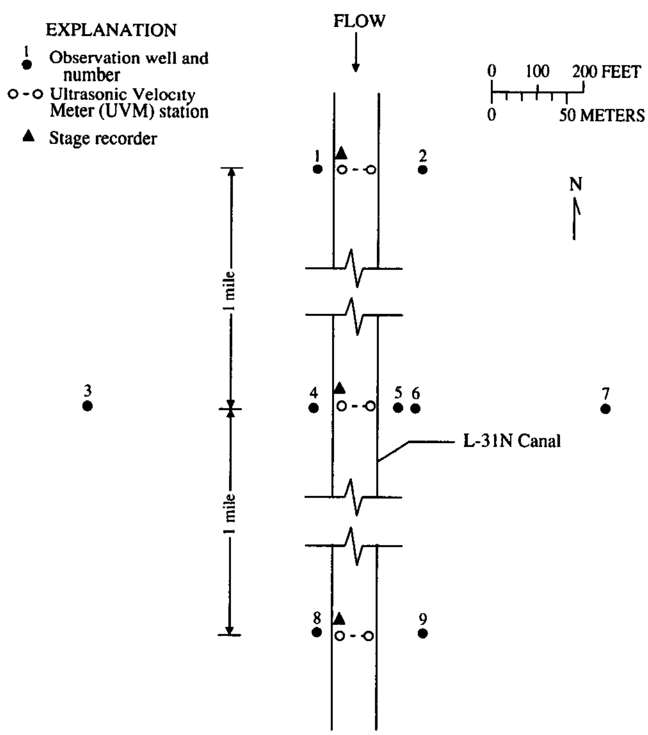

Figure 27. Diagram showing field instrumentation at L–31N canal test reach (Chen, 1990).

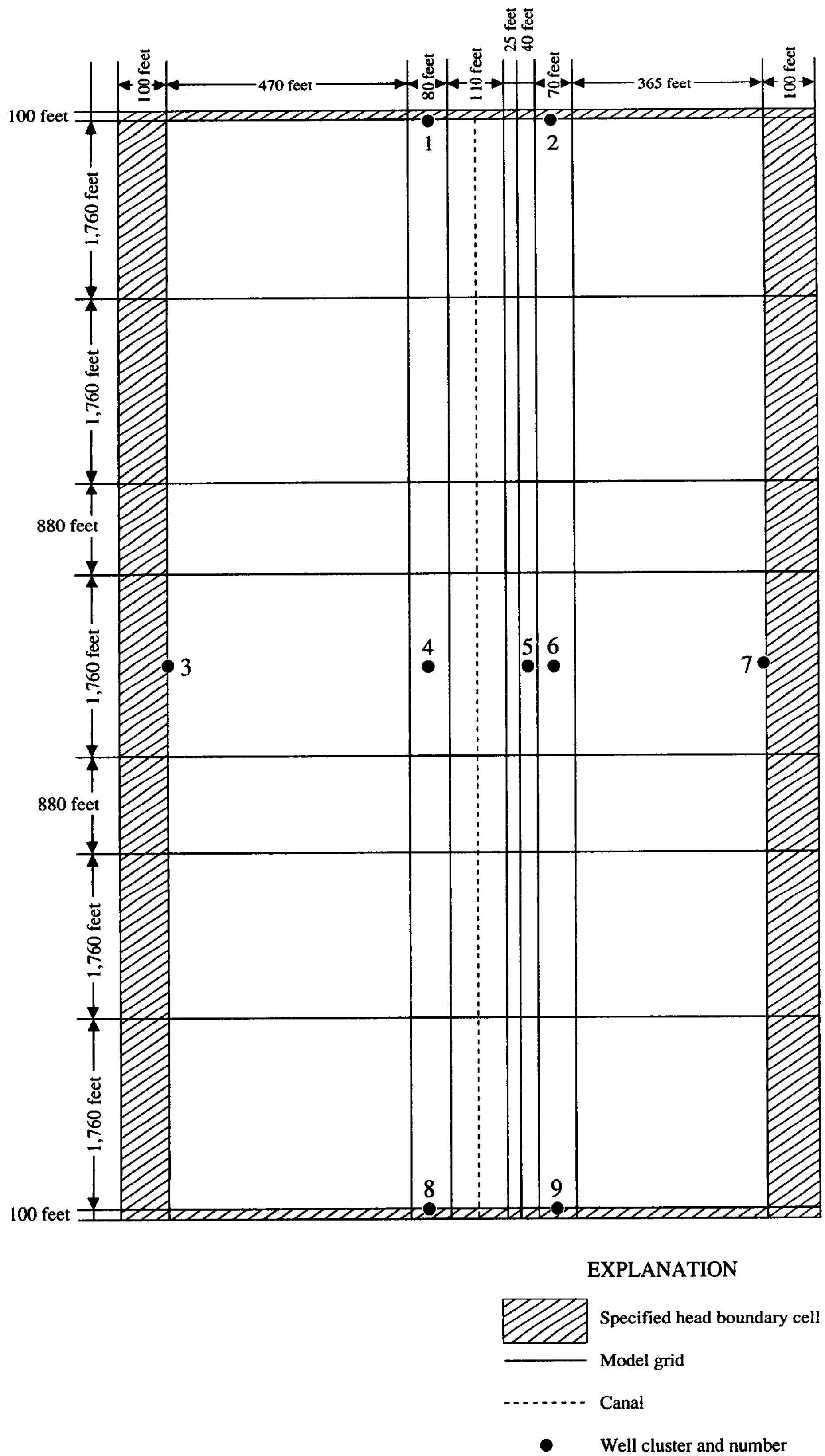

Figure 28. Model aquifer grid for the L–31N canal field problem.

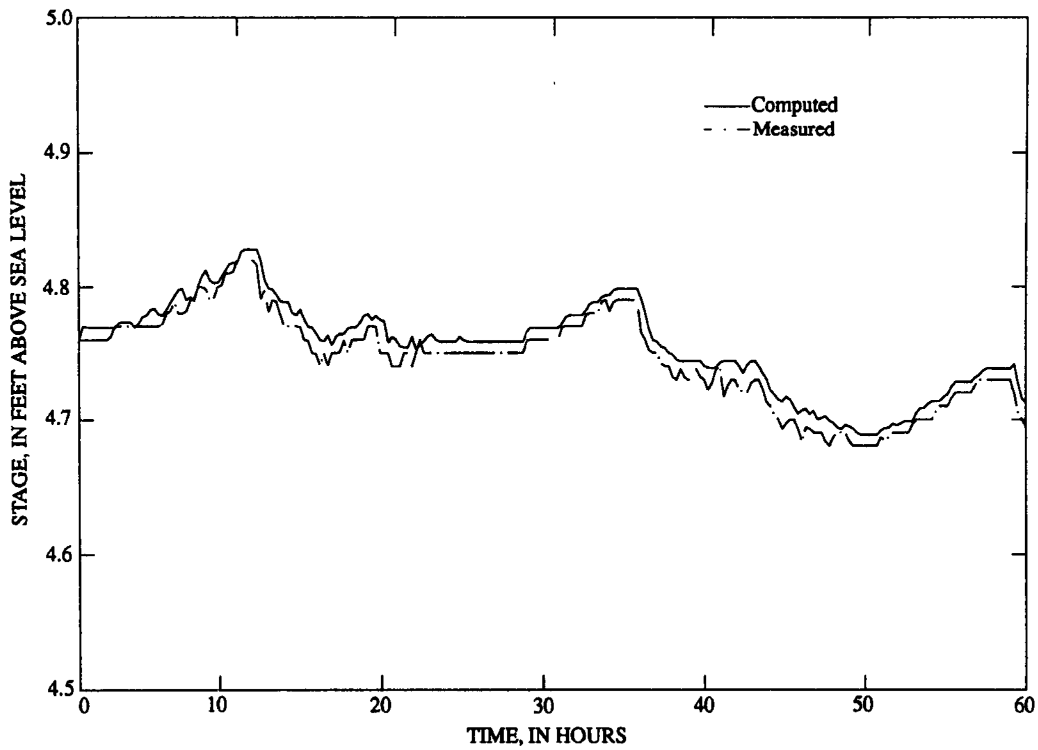

Figure 29. Measured and computed stage at L–31N canal at mile 1.

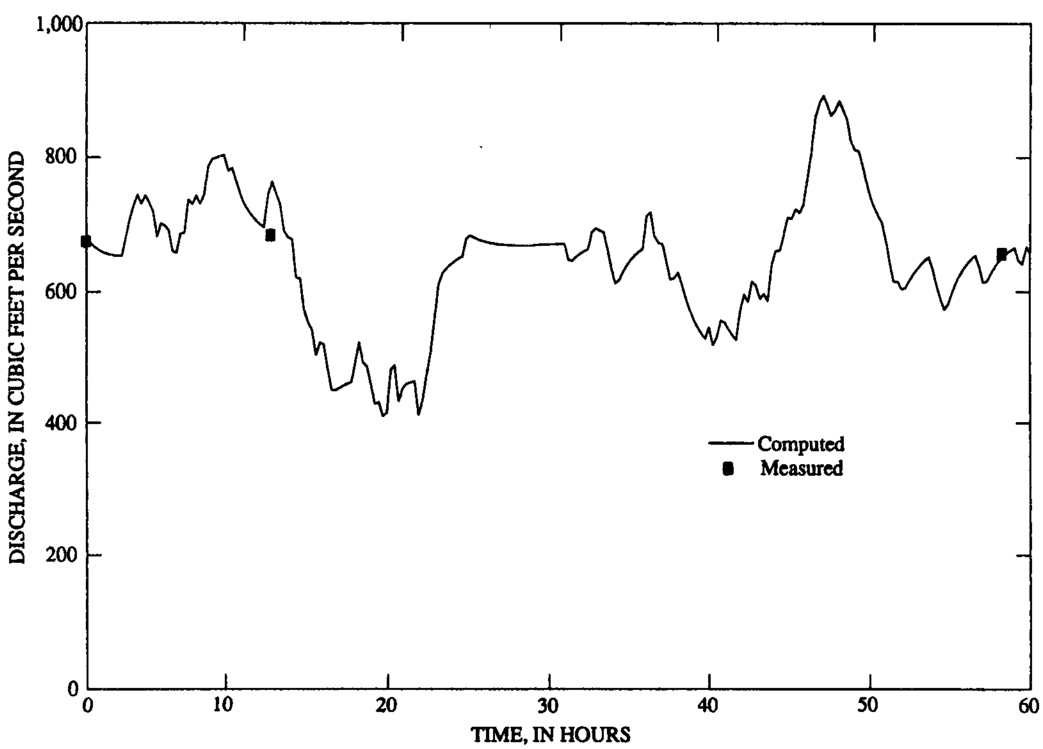

Figure 30. Measured and computed discharge at L–31N canal.

REFERENCES CITED

Chin, D.A., 1990, A method to estimate canal leakage to the Biscayne aquifer, Dade County, Florida: U.S. Geological Survey Water-Resources Investigations Report 90–4135, 32 p.

Faye, R.B., and Mayer, G.C., 1990, Ground-water flow and stream-aquifer relations in the northern coastal plain of Georgia and adjacent parts of Alabama and South Carolina: U.S. Geological Survey Water-Resources Investigations Report 88–4143, 83 p.

Fish, J.E., and Stewart, Mark, 1991, Hydrogeology of the surficial aquifer system, Dade County, Florida: U.S. Geological Survey Water-Resources Investigations Report 90–4108, 50 p., 11 pls.

Hall, F.R., and Moench, A.F., 1972, Application of the convolution equation to stream-aquifer relationships: American Geophysical Union, Water Resources Research, v. 8, no. 2, p. 487–493.

Land, L.F., 1977, Computer program documentation users manual—streamflow routing with losses to bank storage or wells: Bay St. Louis Station, U.S. Geological Survey Computer Contribution Series J–349, 117 p.

Leake, S.A., and Prudic, D.E., 1991, Documentation of a computer program to simulate aquifer-system compaction using the modular finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, chap. A2, 68 p.

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations Report, book 6, chap. A1, 576 p.

Morel-Seytoux, H.J., 1975, Numerical model of flow in a stream-aquifer system: Colorado State University, Hydrology Paper no. 74, 73 p.

Pinder, G.F., and Sauer, S.P., 1971, Numerical simulation of flood wave modification due to bank storage effects: American Geophysical Union, Water Resources Research, v. 7, no. 1, p. 63–70.

Prudic, D.E., 1989, Documentation of a computer program to simulate stream-aquifer relations using a modular, finite difference, ground-water flow model: U.S. Geological Survey Open-File Report 88–729, 113 p.

Roberson, J.A., Cassidy, J.J., and Chaudry, M.H., 1988, Hydraulic engineering: Boston, Houghton Mifflin, 169 p.

Schaffranek, R.W., 1987, Flow model for open-channel reach or network: U.S. Geological Survey Professional Paper 1384, 11 p.

Schaffranek, R.W., Baltzer, R.A., and Goldberg, D.E., 1981, A model for simulation of flow in singular and interconnected channels: U.S. Geological Survey Techniques of Water-Resources Investigations, book 7, chap. C3, 110 p.

Swain, E.D., and Wexler, E.J., 1991, A coupled surface-water and ground-water model: Proceedings of the 1991 National Conference of the Irrigation and Drainage Division, American Society of Civil Engineers, p. 330–335.

Wilson, W.E., 1982, Estimated effects of projected ground-water withdrawals on movement of the saltwater front in the Floridan aquifer, 1976–2000, west-central Florida: U.S. Geological Survey Water-Supply Paper 2189, 24 p.

Yen, B.C., and Riggins, R., 1991, Time scales for surface-subsurface flow modeling: Proceedings of the 1991 National Conference of the Irrigation and Drainage Division, American Society of Civil Engineers, p. 351–358.

Zitta, V.L., and Wiggert, J.M., 1971, Flood routing in channels with bank seepage: American Geophysical Union, Water Resources Research, v. 7, no. 5, p. 1341–1345.

APPENDIXES I–II

APPENDIX I--SAMPLE MODBRANCH INPUT (SELECTED PARTS)

```
        25          5        100          5        720        720       1488
        25          5         20          5        360        288      100.0
TEST CHANNEL RUNNING DRY
EN1920 3   0EN0 100000001 0 000 61.0  0.10.001 0.00.002619617 1.0 00  0.00000100
 1 204REACH 1                                                                  1
    2.125       30.0                 250.0          0.0145
                    1          11         11        0.00100   0.425
 2
2.425        40.     20.                 0.0145
4.425        80.     20.                 0.0145
     2.10       30.0                 500.0          0.0145
                    1          12         11        0.00100   0.4000
 2
2.40         40.     20.                 0.0145
4.40         80.     20.                 0.0145
     2.05       30.0                 500.0          0.0145
                    1          13         11        0.00100   0.3500
 2
2.35         40.     20.                 0.0145
4.35         80.     20.                 0.0145
     2.00       30.0                 500.0          0.0145
                    1          14         11        0.00100   0.3000
 2
2.30         40.     20.                 0.0145
4.30         80.     20.                 0.0145
 2 304REACH 2                                                                  1
     2.00       30.0                 500.0          0.0145
                    1          14         11        0.00100    0.300
 2
2.30         40.     20.                 0.0145
4.30         80.     20.                 0.0145
     1.95       30.0                 500.0          0.0145
                    1          15         11        0.00100    0.250
 2
2.25         40.     20.                 0.0145
4.25         80.     20.                 0.0145
     1.90       30.0                 500.0          0.0145
                    1          16         11        0.00100    0.200
 2
2.20         40.     20.                 0.0145
4.20         80.     20.                 0.0145
     1.85       30.0                 500.0          0.0145
                    1          17         11        0.00100    0.150
 2
2.15         40.     20.                 0.0145
4.15         80.     20.                 0.0145
 3 404REACH 3                                                                  1
     1.85       30.0                 500.0          0.0145
                    1          17         11        0.00100    0.150
 2
2.15         40.     20.                 0.0145
4.15         80.     20.                 0.0145
     1.80       30.0                 500.0          0.0145
                    1          18         11        0.00100    0.100
```

```
 2
2.10          40.      20.                      0.0145
4.10          80.      20.                      0.0145
      1.75       30.0                     500.0          0.0145
                      1          19          11          0.00100     0.050
 2
2.05          40.      20.                      0.0145
4.05          80.      20.                      0.0145
      1.70       30.0                     500.0          0.0145
                      1          20          11          0.00100    0.0001
 2
2.00          40.      20.                      0.0145
4.00          80.      20.                      0.0145
 4 504REACH 4                                                                      1
      1.70       30.0                     500.0          0.0145
                      1          20          11          0.00100    0.0001
 2
2.            40.      20.                      0.0145
4.            80.      20.                      0.0145
      1.65       30.0                     500.0          0.0145
                      1          21          11          0.00100    -0.050
 2
1.95          40.      20.                      0.0145
3.95          80.      20.                      0.0145
      1.60       30.0                     500.0          0.0145
                      1          22          11          0.00100    -0.100
 2
1.90          40.      20.                      0.0145
3.90          80.      20.                      0.0145
      1.55       30.0                     500.0          0.0145
                      1          23          11          0.00100    -0.150
 2
1.85          40.      20.                      0.0145
3.85          80.      20.                      0.0145
 5 604REACH 5                                                                      1
      1.55       30.0                     500.0          0.0145
                      1          23          11          0.00100    -0.150
 2
1.85          40.      20.                      0.0145
3.85          80.      20.                      0.0145
      1.50       30.0                     500.0          0.0145
                      1          24          11          0.00100    -0.200
 2
1.80          40.      20.                      0.0145
3.80          80.      20.                      0.0145
      1.45       30.0                     500.0          0.0145
                      1          25          11          0.00100    -0.250
 2
1.75          40.      20.                      0.0145
3.75          80.      20.                      0.0145
      1.40       30.0                     500.0          0.0145
                      1          26          11          0.00100    -0.300
 2
1.70          40.      20.                      0.0145
3.70          80.      20.                      0.0145
 6 704REACH 6                                                                      1
      1.40       30.0                     500.0          0.0145
                      1          26          11          0.00100    -0.300
```

```
 2
1.70          40.      20.                0.0145
3.70          80.      20.                0.0145
      1.35       30.0              500.0          0.0145
                     1         27         11      0.00100    -0.350
 2
1.65          40.      20.                0.0145
3.65          80.      20.                0.0145
      1.30       30.0              500.0          0.0145
                     1         28         11      0.00100    -0.400
 2
1.60          40.      20.                0.0145
3.60          80.      20.                0.0145
      1.25       30.0              500.0          0.0145
                     1         29         11      0.00100    -0.450
 2
1.55          40.      20.                0.0145
3.55          80.      20.                0.0145
 7 804REACH 7                                                                   1
      1.25       30.0              500.0          0.0145
                     1         29         11      0.00100    -0.450
 2
1.55          40.      20.                0.0145
3.55          80.      20.                0.0145
      1.20       30.0              500.0          0.0145
                     1         30         11      0.00100    -0.500
 2
1.50          40.      20.                0.0145
3.50          80.      20.                0.0145
      1.15       30.0              500.0          0.0145
                     1         31         11      0.00100    -0.5500
 2
1.45          40.      20.                0.0145
3.45          80.      20.                0.0145
      1.10       30.0              500.0          0.0145
                     1         31         11      0.00100    -0.6000
 2
1.40          40.      20.                0.0145
3.40          80.      20.                0.0145
 8 904REACH 8                                                                   1
      1.10       30.0              500.0          0.0145
                     1         32         11      0.00100    -0.6000
 2
1.40          40.      20.                0.0145
3.40          80.      20.                0.0145
      1.05       30.0              500.0          0.0145
                     1         33         11      0.00100    -0.6500
 2
1.35          40.      20.                0.0145
3.35          80.      20.                0.0145
      1.00       30.0              500.0          0.0145
                     1         34         11      0.00100    -0.7000
 2
1.30          40.      20.                0.0145
3.30          80.      20.                0.0145
      0.95       30.0              500.0          0.0145
                     1         35         11      0.00100    -0.7500
```

```
 2
1.25          40.      20.                  0.0145
3.25          80.      20.                  0.0145
 91004REACH 9                                                                      1
      0.95        30.0                 500.0            0.0145
                         1          35          11      0.00100    -0.7500
 2
1.25          40.      20.                  0.0145
3.25          80.      20.                  0.0145
      0.90        30.0                 500.0            0.0145
                         1          36          11      0.00100    -0.8000
 2
1.20          40.      20.                  0.0145
3.20          80.      20.                  0.0145
      0.85        30.0                 500.0            0.0145
                         1          37          11      0.00100    -0.8500
 2
1.15          40.      20.                  0.0145
3.15          80.      20.                  0.0145
      0.80        30.0                 500.0            0.0145
                         1          38          11      0.00100    -0.9000
 2
1.10          40.      20.                  0.0145
3.10          80.      20.                  0.0145
101102REACH 10                                                                     1
      0.80        30.0                 500.0            0.0145
                         1          38          11      0.00100    -0.9000
 2
1.10          40.      20.                  0.0145
3.10          80.      20.                  0.0145
      0.75        30.0                 500.0            0.0145
                         1          39          11      0.00100    -0.9500
 2
1.05          40.      20.                  0.0145
3.05          80.      20.                  0.0145
111204REACH 11                                                                     1
      0.75        30.0                 500.0            0.0145
                         1          39          11      0.00100    -0.9500
 2
1.05          40.      20.                  0.0145
3.05          80.      20.                  0.0145
      0.70        30.0                 500.0            0.0145
                         1          40          11      0.00100    -1.0000
 2
1.00          40.      20.                  0.0145
3.00          80.      20.                  0.0145
      0.65        30.0                 500.0            0.0145
                         1          41          11      0.00100    -1.0500
 2
0.95          40.      20.                  0.0145
2.95          80.      20.                  0.0145
      0.60        30.0                 500.0            0.0145
                         1          41          11      0.00100    -1.1000
 2
0.90          40.      20.                  0.0145
2.90          80.      20.                  0.0145
 11304REACH 12                                                                     1
      2.125       15.0                 353.6            0.0145
                         1          11          11      0.00100    0.425
```

```
 2
 2.425        20.     10.               0.0145
 4.425        40.     10.               0.0145
     2.16       15.0               707.1          0.0145
                   1         10        10         0.00100    0.4600
 2
 2.460        20.     10.               0.0145
 4.460        40.     10.               0.0145
    2.231       15.0               707.1          0.0145
                   1          9         9         0.00100    0.5310
 2
 2.531        20.     10.               0.0145
 4.531        40.     10.               0.0145
    2.302       15.0               707.1          0.0145
                   1          8         8         0.00100    0.6020
 2
2.602         20.     10.               0.0145
4.602         40.     10.               0.0145
131404REACH 13                                                                  1
    2.302       15.0               707.1          0.0145
                   1          8         8         0.00100     0.602
 2
2.602         20.     10.               0.0145
4.602         40.     10.               0.0145
    2.373       15.0               707.1          0.0145
                   1          7         7         0.00100     0.673
 2
2.673         20.     10.               0.0145
4.673         40.     10.               0.0145
    2.444       15.0               707.1          0.0145
                   1          6         6         0.00100     0.744
 2
2.744         20.     10.               0.0145
4.744         40.     10.               0.0145
    2.515       15.0               707.1          0.0145
                   1          5         5         0.00100     0.815
 2
2.815         20.     10.               0.0145
4.815         40.     10.               0.0145
141504REACH 14                                                                  1
    2.515       15.0               707.1          0.0145
                   1          5         5         0.00100     0.815
 2
2.815         20.     10.               0.0145
4.815         40.     10.               0.0145
    2.586       15.0               707.1          0.0145
                   1          4         4         0.00100     0.886
 2
2.886         20.     10.               0.0145
4.886         40.     10.               0.0145
    2.657       15.0               707.1          0.0145
                   1          3         3         0.00100     0.957
 2
2.957         20.     10.               0.0145
4.957         40.     10.               0.0145
    2.728       15.0               707.1          0.0145
                   1          2         2         0.00100     1.028
```

```
 2
3.028         20.     10.                 0.0145
5.028         40.     10.                 0.0145
151603REACH 15                                                                  1
     2.728       15.0              707.1            0.0145
                     1          2          2        0.00100     1.028
 2
3.028         20.     10.                 0.0145
5.028         40.     10.                 0.0145
     2.799       15.0              707.1            0.0145
                     1          1          1        0.00100     1.099
 2
3.099         20.     10.                 0.0145
5.099         40.     10.                 0.0145
     2.870       15.0              707.1            0.0145
                     1          1          1        0.00100     1.170
 2
3.170         20.     10.                 0.0145
5.170         40.     10.                 0.0145
 11704REACH 16                                                                  1
     2.125       15.0              353.6            0.0145
                     1         11         11        0.00100   0.425
 2
2.425         20.     10.                 0.0145
4.425         40.     10.                 0.0145
      2.16       15.0              707.1            0.0145
                     1         10         12        0.00100   0.4600
 2
2.460         20.     10.                 0.0145
4.460         40.     10.                 0.0145
     2.231       15.0              707.1            0.0145
                     1          9         13        0.00100   0.5310
 2
2.531         20.     10.                 0.0145
4.531         40.     10.                 0.0145
     2.302       15.0              707.1            0.0145
                     1          8         14        0.00100   0.6020
 2
2.602         20.     10.                 0.0145
4.602         40.     10.                 0.0145
171804REACH 17                                                                  1
     2.302       15.0              707.1            0.0145
                     1          8         14        0.00100     0.602
 2
2.602         20.     10.                 0.0145
4.602         40.     10.                 0.0145
     2.373       15.0              707.1            0.0145
                     1          7         15        0.00100     0.673
 2
2.673         20.     10.                 0.0145
4.673         40.     10.                 0.0145
     2.444       15.0              707.1            0.0145
                     1          6         16        0.00100     0.744
 2
2.744         20.     10.                 0.0145
4.744         40.     10.                 0.0145
     2.515       15.0              707.1            0.0145
                     1          5         17        0.00100     0.815
```

```
 2
2.815        20.     10.                 0.0145
4.815        40.     10.                 0.0145
181904REACH 18                                                                 1
     2.515       15.0             707.1          0.0145
                     1          5         17          0.00100     0.815
 2
2.815        20.     10.                 0.0145
4.815        40.     10.                 0.0145
     2.586       15.0             707.1          0.0145
                     1          4         18          0.00100     0.886
 2
2.886        20.     10.                 0.0145
4.886        40.     10.                 0.0145
     2.657       15.0             707.1          0.0145
                     1          3         19          0.00100     0.957
 2
2.957        20.     10.                 0.0145
4.957        40.     10.                 0.0145
     2.728       15.0             707.1          0.0145
                     1          2         20          0.00100     1.028
 2
3.028        20.     10.                 0.0145
5.028        40.     10.                 0.0145
192003REACH 19                                                                 1
     2.728       15.0             707.1          0.0145
                     1          2         20          0.00100     1.028
 2
3.028        20.     10.                 0.0145
5.028        40.     10.                 0.0145
     2.799       15.0             707.1          0.0145
                     1          1         21          0.00100     1.099
 2
3.099        20.     10.                 0.0145
5.099        40.     10.                 0.0145
     2.870       15.0             707.1          0.0145
                     1          1         21          0.00100     1.170
 2
3.170        20.     10.                 0.0145
5.170        40.     10.                 0.0145
 Q16 72  11447500 FROM- 90/10/01 08:00  TO- 90/10/02  1:45 8    96
      -15.      -10.0      -5.4       0.0       0.0       0.0       0.0       0.0
       0.0        0.0       0.0       0.0       0.0       0.0       0.0       0.0
       0.0        0.0       0.0       0.0       0.0       0.0       0.0       0.0
       0.0        0.0       0.0       0.0       0.0       0.0       0.0       0.0
       0.0        0.0       0.0       0.0       0.0       0.0       0.0       0.0
       0.0        0.0       0.0       0.0       0.0       0.0       0.0       0.0
       0.0        0.0       0.0       0.0       0.0       0.0       0.0       0.0
       0.0        0.0       0.0       0.0       0.0       0.0       0.0       0.0
       0.0        0.0       0.0       0.0       0.0       0.0       0.0       0.0
 Q20 72  11447514 FROM- 90/10/01 08:00  TO- 90/10/02  1:45 8    96
      -15.      -10.0      -5.4       0.0       0.0       0.0       0.0       0.0
       0.0        0.0       0.0       0.0       0.0       0.0       0.0       0.0
       0.0        0.0       0.0       0.0       0.0       0.0       0.0       0.0
       0.0        0.0       0.0       0.0       0.0       0.0       0.0       0.0
       0.0        0.0       0.0       0.0       0.0       0.0       0.0       0.0
       0.0        0.0       0.0       0.0       0.0       0.0       0.0       0.0
       0.0        0.0       0.0       0.0       0.0       0.0       0.0       0.0
       0.0        0.0       0.0       0.0       0.0       0.0       0.0       0.0
       0.0        0.0       0.0       0.0       0.0       0.0       0.0       0.0
ZP12
```