SPECIAL PUBLICATION SJ2008-SP23

KARST AQUIFER MODELING IN NORTH-CENTRAL FLORIDA REVISION 1

KARST AQUIFER MODELING IN NORTH-CENTRAL FLORIDA
REVISION 1

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Prepared for:

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May 2008

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ACKNOWLEDGMENTS

This project was funded by the University of Florida. Dr. Kirk Hatfield of the Department of Civil and Coastal Engineering at the University of Florida is acknowledged for his efforts in planning and executing the project. Mr. Stan Williams of the St. Johns River Water Management District is thanked for providing technical assistance with regard to the hydrogeology of Volusia County and vicinity and for sharing his knowledge of the existing MODFLOW groundwater flow model. Ms. Lili Yu and Dr. Kirk Hatfield are thanked for their analyses of correlations and statistical analysis of precipitation, groundwater elevations, and spring discharge. Dr. Scott Painter is thanked for his thorough review and assessment of the MODFLOW-DCM model. A constructive review by Dr. Gary Walter improved the quality of this report. Ms. Cheryl Patton is thanked for her assistance with report preparation.

EXECUTIVE SUMMARY

The Civil and Coastal Engineering Department at the University of Florida was retained by the St. Johns River Water Management District to evaluate the dynamic hydraulic response of a karst aquifer in north-central Florida using innovative analyses and quantitative tools. This project was motivated by the need of the St. Johns River Water Management District to manage water resource caution areas (i.e., areas where existing or future anticipated water resources are deemed insufficient to satisfy current or projected demands over a 20-year planning period). The area of interest is the springshed that provides for Blue Spring in Volusia County in northeast Florida. The University of Florida retained Southwest Research Institute® in this investigative endeavor.

The critical components of the assessment included an evaluation to determine whether MODFLOW-DCM Version 2.0 (Painter et al., 2007) improves existing models, whether the improvements adequately capture the hydraulic dynamics of the karst groundwater flow system, and whether these are useful in groundwater resource management. MODFLOW-DCM is an innovative numerical simulator designed to account for the dynamic interaction between diffuse and conduit flow inherent in karst aquifers. This evaluation also determined whether MODFLOW-DCM could characterize a karst aquifer in which conduits are poorly located and characterized.

Williams (2006) standard MODFLOW model for Volusia County was converted into a dual continuum model in an attempt to account for both slow diffuse flow and rapid conduit flow that the Floridan Aquifer exhibited. Capturing both flow regimes in groundwater flow models is important to replicating the dynamic response of Blue Spring to recharge and pumping. The dual continuum model MODFLOW-DCM Version 2.0 was used in the simulations.

The MODFLOW-DCM version of the Volusia County groundwater model was constructed with a conduit network embedded in a diffuse layer to capture the flow system that discharges at Blue Spring. Data available for evaluating the model included groundwater elevation measurements taken at three index wells and discharge measurements at Blue Spring. Measurements at the index wells are believed to be sufficiently accurate, but all three index wells are near Blue Spring and there were no well data from other regions of the model domain to indicate aquifer response in those areas to changes in recharge and pumping. Uncertainty in discharge rates from Blue Spring resulted from incomplete records of discharge for the target period of performance.

The redefined conduit/diffuse layer model replicated the dynamic response of spring discharge and groundwater elevations to seasonal changes in precipitation, but the transient model was not calibrated. The MODFLOW-DCM model approximately replicated the Blue Spring discharge hydrograph during high recharge events, although baseflow discharge and the lag between rainfall and discharge were not successfully reflected in the model simulations. Baseflow discharge at Blue Spring was underpredicted by about 40 percent in the basecase simulation. Replication of groundwater elevations at an index well near Blue Spring and an index well in the DeLand Ridge, which is within the suspected area of recharge for Blue Spring, was more successful than replication of groundwater elevations in an area south of Blue Spring, which is not believed to be an area of significant recharge for Blue Spring. Groundwater elevations at the Blue Spring and DeLand wells were generally overpredicted, while heads at the well to the south of Blue Spring were underpredicted. These discrepancies indicate that model conduit locations relative to the wells or the hydraulic conductivity values assigned to the diffuse layer need modification.

Sensitivity analysis results highlighted the relative effects that changes in conduit conductivity, diffuse layer hydraulic conductivity, recharge distribution and intensity, and storage coefficient have on model performance. In general, the MODFLOW-DCM version of the Volusia County groundwater flow model responded to these changes; however, target hydraulic head data at additional locations in the model domain and a more complete record of spring discharge would be beneficial, if not required, to effectively calibrate the transient model.

Additional tasks to improve the model have been identified. The nature and extent of the conduit network in the dual continuum model should be enhanced. During this evaluation, the conduit network was expanded in a piecemeal fashion to test model performance response to increased springshed size. The effect of expanding the conduit network to include more of the DeLand ridge recharge zone should be evaluated. Conduit networks should be added for the other major springs in the model domain. A more representative conduit network can be predicated using mapped cave geometries of other conduit systems in the Floridan Aquifer in north-central and northeast Florida. Geomorphological and hierarchical analysis techniques developed for surface rivers and streams could also be used to identify a subsurface conduit network.

The effect of epikarst and the relatively large size of the recharge (springshed) zone should be examined. It is likely that the epikarst hydraulically affects the lag observed in spring discharge and groundwater elevations observed at the index wells. This recommendation is challenging because the dual continuum conceptualization in MODLFOW-DCM is limited to a single layer model. The effect of delayed flow through the epikarst may need to be accounted for by *a priori* adding a delay in the timing of recharge. Correlation analysis among spring discharge, groundwater elevation, and precipitation should be expanded to include wells and springs over a larger geographical area. Correct replication of hydraulic lag in spring discharge may be resolved when the conduit network is modified to account for the full extent of the springshed.

1. Introduction

The Civil and Coastal Engineering Department at the University of Florida was retained by the St. Johns River Water Management District (SJRWMD) to evaluate the dynamic hydraulic response of a karst aquifer in north-central Florida using innovative analyses and quantitative tools. This project was motivated by the need of the SJRWMD to manage water resource caution areas (i.e., areas where existing or future anticipated water resources are deemed insufficient to satisfy current or projected demands over a 20-year planning period) (St. Johns River Water Management District, 2005a,b; Kinser et al., 2006). The area of interest is the springshed that provides for Blue Spring in Volusia County in northeast Florida. The University of Florida retained Southwest Research Institute® in this investigative endeavor.

The critical components of the assessment include an evaluation to determine whether MODFLOW-DCM Version 2.0 (Painter et al., 2007) improves existing models, whether the improvements adequately capture the hydraulic dynamics of the karst groundwater flow system, and whether these are useful in groundwater resource management. MODFLOW-DCM is an innovative numerical simulator designed to account for the dynamic interaction between diffuse and conduit flow inherent in karst aquifers. This evaluation also determined whether MODFLOW-DCM could simulate the hydraulic response of a karst aquifer in which conduits are poorly located and characterized.

2. Objectives

The objectives of the project were as follows:

1) Perform simulations of a karst aquifer site in north-central Florida using MODFLOW-DCM Version 2.0 (Painter et al., 2007) to evaluate whether the dynamic hydraulic response of the karst system can be captured with a numerical model. A critical component to the evaluation was whether MODFLOW-DCM sufficiently improves existing models and whether the improvements adequately capture the hydraulic dynamics of the karst groundwater flow system and whether these are useful as a groundwater resource management tool.
2) Transfer technology from the SwRI research team to the funding agencies (University of Florida and the SJRWMD) through technical interactions.

3. Scope of Work

Two candidate sites were identified at the onset of the project for application of MODFLOW-DCM: Blue Spring and Silver Springs. Both sites are located in north-central Florida and are within the jurisdiction of the SJRWMD. The scope of this modeling project was predicated on the assumption that a viable MODFLOW model of the candidate site was available at the onset of the project. If a preexisting MODFLOW model was unavailable or was inappropriate, then the parties would have selected an alternate site to apply MODFLOW-DCM. Similarly, if neither of these locations were appropriate for study in this project for any other reason, other candidate sites would have been considered for applying MODFLOW-DCM. An alternative site was mutually agreed on by the SJRWMD and the University of Florida. Early assessment indicated that the SJRWMD Volusia County and vicinity model (Williams, 2006) was appropriate for modeling the Blue Spring system.

This project focused on developing a transient model of the groundwater system capable of simulating spring discharge and aquifer response times on the order of a day due to storm events. The quality of available rainfall records, spring discharge hydrographs, and groundwater elevation data at select wells proved to be key in the analysis.

A standard MODFLOW model for the selected study site was converted from a single diffuse system to a dual continuum model (DCM) system as defined in MODFLOW-DCM Version 2.0 (Painter et al., 2007). The utility of the DCM conceptual model was tested for transient conditions. The transient model included a conduit layer and a diffuse aquifer layer consistent with MODFLOW-DCM. To achieve the project objectives, telescope mesh refinement (TMR) was determined to be unnecessary and was not used. The model was calibrated, to the degree possible, using available time-series records of rainfall, groundwater levels, and spring discharges. Important model calibration parameters included recharge distribution and rate, diffuse-layer hydraulic conductivity, conduit network, conduit conductivity, and depending on whether the aquifer was assumed confined or unconfined, conduit storativity (or specific yield) and diffuse aquifer storativity (or specific yields). The project duration was 25 months with a completion date of May 31, 2008.

4. Task Identification

Project tasks were as follows:

Task 1: Data assembly – Existing standard MODFLOW models were evaluated for use as the starting foundation of this project. The scope of effort required for data assembly was contingent on the study site and the specific MODFLOW model selected for analysis.

Task 2: Initial MODFLOW-DCM model construction and testing – The primary modification of the standard MODFLOW model data set was to parse out the matrix continuum and the conduit network from the preexisting, single continuum characterization of the medium. Available time-series records of rainfall, groundwater elevations, and spring discharges were to be divided into two sets: one for model calibration and the other for model validation. Insufficient data were available for model validation at this time. The model was developed to predict transient fluctuations in both groundwater levels and spring discharge derived from storm events and/or seasonal precipitation variations. Important model calibration parameters included recharge distribution and rate, diffuse-layer hydraulic conductivity, conduit network, conduit conductivity, and depending on whether the aquifer was assumed confined or unconfined, conduit storativity (or specific yield) and diffuse aquifer storativity (or specific yields).

Task 3: MODFLOW-DCM model refinement – The importance and appropriateness of representing conduits in MODFLOW-DCM using discrete features was evaluated through sensitivity analysis. By including a conduit network, the MODFLOW-DCM model diffuse layer transmissivities were lower than the Williams (2006) groundwater model to be more typical of the diffuse aquifer zone. This is because a portion of the subsurface flow with high transmissivities was apportioned to the conduits. The density of the conduit network was also examined.

Task 4: Model evaluation – - Conduit representation was the most critical component in the model. Matching of model results to the physical system was evaluated in terms of hydraulic head, recharge, and discharge rates. A sensitivity analysis was conducted to ascertain how changes in these parameters affected predictions of groundwater head and spring flows.

Task 5: Technology transfer – The project team provided the SJRWWMD staff with a final report, model input data, and a final oral presentation of project findings. SJRWMD staff participated in the project, but was not assigned tasks nor were they responsible for activities considered central to the critical path of the project.

Task 6: Reporting – The project team provided quarterly progress reports summarizing the financial status and technical progress of the project. A final report was prepared at the conclusion of the project. The final report includes a description of the site model, including the simulation results. The relative success of MODFLOW-DCM to simulate conduit flow through a karst aquifer with relatively high matrix permeability is assessed and discussed in the final report.

5. Study Site Selection

Existing standard MODFLOW models of the Blue Spring and Silver Springs areas were evaluated for use in this analysis (Shoemaker et al., 2004; Williams, 2006). The preexisting MODFLOW model for the Volusia County area (Williams, 2006) was identified as appropriate for this project and was used as the starting point for the MODFLOW-DCM model. Data Williams (2006) assembled were used to construct the MODFLOW-DCM model for the Blue Spring area. The Williams (2006) groundwater model is considered a fourth-generation model of the study area, and it effectively integrates the data and findings from previous studies with unpublished data from the files of U.S. Geological Survey, SJRWMD, and related local sources.

The study site essentially encompasses Volusia County and adjacent areas in north-central Florida. The boundaries of this investigation coincide with the boundaries of the groundwater flow model of Williams (2006) (Figure 1). The dimensions of the study site are 250,000 feet × 250,000 feet. The study area includes essentially all of Volusia County, with the exception of a small segment located southeast of Lake Hamey, and includes small parts of Brevard, Seminole, Orange Lake, Putnam, and Flagler Counties.

6. Background and Previous Investigations

The hydrogeology and the water resources of the Volusia County area have been extensively investigated in recent years. Motivating these studies are the competing interests of water demand required by commercial and residential development against the needs to protect critical sensitive environmental features of north-central Florida. Foremost are requirements to protect natural refuges for the manatee. Manatees seek refuge in the warmer waters of the Blue Spring Run when the temperature of the river drops below 68°F (20°C) (St. Johns River Water Management District, 2008). The Blue Spring Run is a ¼-mile-long stream that connects Blue Spring with the St. Johns River. The warm-water refuge that the Blue Spring Run offers becomes impacted when (1) spring discharge is decreased due to pumping in the springshed of Blue Spring and (2) the 68°F (20°C) isotherm in the Blue Spring Run migrates toward the spring, thereby decreasing the size of the warm-water refuge (Kinser et al., 2006).

Wyrick (1960), Knochenmus and Beard (1971), Bush (1978), Rutledge (1982, 1985a,b), and Kimrey (1990) performed comprehensive investigations of the hydrogeology of Volusia County. These studies and others (Wyrick, 1961; Laughlin and Hughes, 1971; Munch, 1979; Munch et al. 1980; and Knochenmus and Robinson, 1996) provided compilations of water-level data and estimates of aquifer hydraulic characteristics for the Volusia County area. White (1970) and Knochenmus (1968) investigated surficial geology. Johnson (1981) and Miller (1986) characterized the structural geology.

Bush (1978) developed the first groundwater model of Volusia County which provided a framework used in most subsequent modeling efforts. Tibbals (1981, 1990) developed a regional numerical groundwater model of east-central Florida. Geraghty and Miller (1991) included the surficial aquifer system in their model of the Floridan Aquifer. Huang and Williams (1996) developed an iterative procedure to couple the surficial and Floridan aquifers in Volusia County. Williams (1997) refined the Geraghty and Miller (1991) conceptualization that included the surficial and the Floridan aquifer systems. Durden (2000) assessed regional drawdown using a numerical model. Molz and Dogan (2004) developed a regional-scale groundwater model of north-central Florida. Williams (2006) groundwater model and supporting analyses synthesized most of the earlier hydrogeology-related investigations in Volusia County. Williams (2006) standard MODFLOW model was used as the basis for the analyses performed as part of this investigation.

Recharge values used in this analysis were taken from several sources. Wyrick (1960) relied on relative water-table elevations in the surficial aquifer and the Upper Floridan Aquifer to indicate zones either conducive or unfavorable to recharge of the Upper Floridan Aquifer. Boniol et al. (1993) assessed recharge to the Upper Floridan Aquifer by correlating land surface with measured water-table elevations. Rutledge (1985a) and Vecchioli et al. (1990) calculated recharge using water-budget analyses. Williams (2006) noted that areas with low recharge to the Upper Floridan Aquifer are typically in low-lying terraces where the vertical hydraulic gradient is small or where the intermediate confining layer is relatively thick or of low permeability. Painter et al. (2007) used

MODFLOW-DCM to assess documented values of recharge of confined and unconfined areas of the Upper Floridan Aquifer in the Santa Fe sink/rise system in west-central Florida. Insight provided by this model helped assess recharge in Volusia County.

7. Physiography

7.1 Climate

The climate of Volusia County is classified as humid subtropical (Phelps, 1990). The average annual temperature is 70.4°F (21.3°C), and the average annual rainfall is 54.57 inches at DeLand (Phelps, 1990). Nearly 60 percent of the annual rainfall is from June through October when precipitation occurs as localized convective thunderstorms (Rao et al., 1997). Because of the convective thunderstorms, rainfall patterns are spatially and temporally distributed unevenly (Williams, 2006).

Evapotranspiration represents the largest relative loss of water that could otherwise provide recharge. Evapotranspiration is a function of geology, depth to water, soil, and vegetation. In Volusia County, it varies from a low of 25 to 35 inches/year where soils are deep and well drained or where karst features such as sinkholes are predominant (Knochenmus and Hughes, 1976; Tibbals, 1977; Williams, 2006) to a high of 46 inches/year where the water table is shallow and soils are organic (Visher and Hughes, 1975; Kohler et al., 1959). County-wide evapotranspiration values are expected to average between 35 and 39 inches/year (Knochenmus and Beard, 1971; Rutledge, 1985a; Williams, 2006). Estimated ranges of the water budget components for the surficial aquifer are summarized in Table 1.

7.2 Topography

The physiography of Volusia County can be described as a series of terraces oriented subparallel to the Atlantic Ocean coastline (Wyrick, 1960). There are four prominent terraces present in Volusia County, which formed when sea level was higher than present day and when sea level remained constant for a sufficient time (Figure 2). The terraces emerged as level plains after the sea level dropped. The seaward edge of the terrace then became the shoreline for the lower and more recent terrace.

The four terraces in Volusia County — Penholoway, Talbot, Pamlico, and Silver Bluff — are of Pleistocene age (Figure 2). The oldest terrace, located about 20-35 miles inland, is the Penholoway Terrace with a surface elevation of 70 to 80 feet above sea level. Next oldest is the Talbot Terrace, located 10-20 miles inland, with an elevation of about 45 feet above sea level. Third oldest is the Pamlico Terrace, located about 5-10 miles inland, with an elevation of 25 to 30 feet above sea level. The Silver Bluff Terrace is found at the shoreline and has an elevation of 5-6 feet above sea level (Wyrick, 1960).

The terraces are mostly level with the exception of the Penholoway Terrace, which exhibits significant karst development (Wyrick, 1960). Karst development on the Penholoway Terrace is characterized by high local relief, sinkhole lakes and ponds, dry depressions, and subsurface drainage. Topographic elevation on the Penholoway Terrace varies from 110 feet (msl) near Deltona to as low as 10 feet (msl) in depressions near Orange City (Knochenmus and Beard, 1971). Extensive karst development extends from the DeLand Ridge north to the Crescent City Ridge, all of which is part of the

Penholoway Terrace (Wyrick, 1960). The epikarst on the Penholoway Terrace allows for rapid infiltration with essentially no surface water runoff. There are about 120 lakes in Volusia County; 90 percent are located on the Penholoway Terrace (Knochenmus and Beard, 1971).

There is no evidence of karst development on Talbot, Pamlico, and Silver Bluff terraces in Volusia County (Knochenmus and Beard, 1971). These terraces are flat, poorly drained, covered with forest vegetation, and commonly referred to as flatwoods. Because of these contrasting conditions, river and stream development is extensive in the flat-woods areas and nonexistent in karst terrains. An important subfeature has developed on the seaward side of the Talbot, Pamlico, and Silver Bluff terraces (Knochenmus and Beard, 1971). These are ridges formed as shoreline ridges that now act as local reservoirs for groundwater storage and sources of recharge for the underlying Upper Floridan Aquifer (Knochenmus and Beard, 1971). Rima Ridge rises about 5 to 10 feet on the seaward side of Talbot Terrace; Atlantic Coastal Ridge rises about 10 to 15 feet on the seaward side of Pamlico Ridge; and the Atlantic Beach Ridge, which rises about 10 feet above Silver Bluff Terrace, is currently forming on the seacoast. Formation of the terraces and ridges has forced most streams and river formations to be oriented north-south. Exceptions are Tomoka River and Spruce Creek, which flow directly into the ocean and provide an increased opportunity for saltwater intrusion.

7.3 Geology and Hydrostratigraphy

The study area geology consists of carbonate formations overlain by surficial clastic sediments made up of poorly consolidated sand, clay, and shell of Pleistocene to Miocene age (Knochenmus and Beard, 1971 and Davis et al., 2001)(Table 2). The carbonate formations form the Floridan Aquifer, which varies in age from Oligocene to Eocene. There are three recognized significant aquifers in the study region: the surficial aquifer, the Upper Floridan Aquifer, and the Lower Floridan Aquifer. There are two confining layers of significance; the intermediate confining layer overlying the Floridan Aquifer and the middle confining unit separating the Upper Floridan Aquifer from the Lower Floridan Aquifer.

Beds within the clastic sediments tend to be discontinuous, lenticular, and interfingering (Knochenmus and Beard, 1971). In general, the clastic sediments are fine sands underlain by clay lenses deposited on shell beds that directly overly the carbonate rocks. This depositional environment varies widely, but tends to form the upper confining layer and limits the rate of recharge to the Upper Floridan Aquifer in areas where with significant clay sediments. A discontinuous surfical aquifer is present in the clastic sediments. The Upper Floridan Aquifer includes the Suwannee Limestone, Ocala Limestone, and the upper portion of the Avon Park Formation (Table 2). The lower portion of the Avon Park Formation and the Oldsmar Formation form the Lower Floridan Aquifer. The Lower Floridan Aquifer is not typically used for water supply due to its poor quality water.

Groundwater availability and flow can be significantly dependent on geologic structure. This can be particularly true in a karst aquifer, such as the Upper Floridan Aquifer, because karst features, such as conduits, may develop along geological structural features. Of interest is a geologic framework model of the Lower Floridan Aquifer Duncan et al. (1994) developed. In this study, Duncan et al. identify a basement normal fault closely aligned with St. Johns River. Although speculative, this fault location may have influenced alignment of the current St. Johns River. This basement fault does not appear to penetrate through the Upper Floridan Aquifer formations.

The central portion of the Upper Floridan Aquifer in Volusia County has been characterized as an uplifted fault block (Wyrick, 1960; Knochenmus and Beard, 1971). Bedding of this block dips to the east at a slope of 3 feet/mile (Wyrick, 1960). The western edge of the block is defined by a north-trending fault located west of DeLand (Knochenmus and Beard, 1971) passing through Ponce de Leon Springs. This fault separates a structural dome near Pierson from a structural high near DeLand. The north end of the block is defined by an east-trending fault at the north end of Lake Monroe with 60 to 100 feet of displacement (Wyrick, 1960). The eastern edge of the block is bounded by a north-trending fault located 5-15 miles from the coastline and extending north from Brevard County (Brown et al., 1962). This geologic framework of the Upper Floridan Aquifer is important because the four major faults that permeate the Upper Floridan Aquifer could provide preferred channels for conduit development. Of particular interest is the potential for development of a north-trending conduit responsible for the groundwater trough located subparallel and east of the St. John River.

8. Hydrology

8.1 Recharge

Recharge of the Upper Floridan Aquifer in Volusia County is a function of the hydraulic head difference between the surficial aquifer and the Upper Floridan Aquifer and hydraulic properties of the intermediate confining unit that separates the two aquifers. Estimating recharge is problematic because of the uncertainty in measuring each of these integral components. In addition, recharge varies spatially and in terms of magnitude. Neither is well defined. Recharge estimates are subject to the conceptual model on which they are predicated. Various approaches have been taken to (1) determine the integral components used to calculate recharge or (2) directly measure or estimate a representative value for recharge. Wyrick (1960) relied on relative groundwater elevations of the surficial aquifer and the Upper Floridan Aquifer to indicate zones either conducive or unfavorable to recharge of the Upper Floridan Aquifer. He noted that only zones with water elevations that were higher in the surficial aquifer than in the Upper Floridan Aquifer would result in recharge to the Upper Floridan Aquifer. Areas where the groundwater elevation of the Upper Floridan Aquifer is greater than in the surficial aquifer would be better candidates to be discharge zones for the Upper Floridan Aquifer. Wyrick (1960) identified zones where wells in the Upper Floridan Aquifer are flowing (indications of zones of discharge) in a 2 to 3 mile-wide belt along the Atlantic Ocean coast, in the lowlands adjacent to Tomoka River and Spruce Creek, and along St. Johns River extending from Brevard County in the south to Lake George in the north. This zone is approximately 8 miles wide near Ponce de Leon Springs, but less wide elsewhere (Wyrick, 1960).

Boniol et al. (1993) assessed recharge to the Upper Floridan Aquifer by correlating land surface elevations with measured water-table elevations to estimate recharge values that ranged from 0 to 2 inches/year in low-lying areas to over 16 inches/year in upland ridges. Williams (2006) noted that areas with low recharge to the Upper Floridan Aquifer are typically in low-lying terraces where the vertical hydraulic gradient is small or where the intermediate confining layer is relatively thick or of low permeability. Conversely, high rates of recharge to the Upper Floridan Aquifer occur in the sandy upland ridges where the vertical hydraulic gradient is relatively high and where the intermediate confining layer is thin or has relatively high permeability.

Rutledge (1985a) calculated recharge using a water-budget analysis to be 0, 4, 10, and 18 inches/year for areas of artesian flow, nonridge areas without artesian flow, ridge areas with surface drainage, and ridge areas with closed basins, respectively. Rutledge (1985a) designated two drainage areas that contribute to Blue Spring. Area 3 covered 138 mi^2 to the east of Blue Spring and encompassed the DeLand Ridge and nearby areas. Rutledge (1985a) classified the 138-mi^2 area as 1 percent artesian, 29 percent nonridge areas without artesian flow, 12 percent ridge areas having surface drainage, and 58 percent ridge areas in closed basins. Rutledge (1985a) calculated that the equivalent of 130 cubic feet/second (cfs) of the discharge at Blue Spring was contributed by recharge in Area 3. The area-weighted average recharge for Area 3 was calculated as 12.8 inches/year. Area

4 covered 59 mi^2 to the west of Blue Spring, most of which was in Lake County. Rutledge (1985a) calculated that the equivalent of 9.4 cfs was contributed by recharge in Area 4 to discharge at Blue Spring. This equates to an areal recharge rate of 2.16 inches/year in Area 4.

Vecchioli et al. (1990) estimated the approximate area of the Blue Spring basin to be 268 mi^2 of which 46 mi^2 was deemed to be discharge area with artesian flow. They calculated the approximate area of internally drained terrain in the spring basin to be 121 mi^2. If recharge is assumed to provide all Blue Spring discharge in the 121 mi^2 area, an annual rate of 17.9 inches/year of recharge is implied. Similarly, Vecchioli et al. (1990) calculated the recharge rate for the Ponce de Leon Springs to be 18.4 inches/year over an area of 21.6 mi^2.

8.2 Spring Discharge

There are 11 springs in the study area with an average discharge of 1 cfs or greater (German, 2004; Williams, 2006) (Table 3). Of these, Blue Spring is the largest and the only first-magnitude spring (i.e., > 100 cfs). Using instantaneous discharge measurements, the U.S. Geological Survey and the SJRWMD determined discharge from Blue Spring since March 1932 and from February 1983 to February 1996, respectively (Osburn, 2007). Instantaneous discharge measurements are calculated using current velocity measurements. Currently, the U.S. Geological Survey and SJRWMD staffs also take instantaneous manual flow measurements at monthly or bimonthly intervals. The average flow for calendar year 2005 was 175 cfs. The measured discharge at Blue Spring has ranged from a minimum of 87 cfs in November 2001 to a maximum of 218 cfs in February 1983 (St. Johns River Water Management District, 2008). The long-term average discharge of Blue Spring is 157 cfs calculated from 654 instantaneous manual flow measurements the U. S. Geological Survey and the SJRWMD collected and compiled over a 75-year period of record (St. Johns River Water Management District, 2008).

Osburn (2007) has evaluated the accuracy of these data sets. These data are summarized in Figure 3 (Osburn, 2007). Rapid changes in discharge rates (commonly referred to as “flashiness of a spring”) at Blue Spring cannot be discerned from Figure 3, but several general discharge attributes of the spring are clear. The median flow for this period of record is approximately 158 cfs. The 5th and 95th quantiles are 122 and 186 cfs, respectively. There was a period of low flow around 1990 and high flows in 1950s and 1960s with a short duration of high flow in 2005. During the period between November 1991 and October 2007, manual discharge measurements had a median of 151 cfs with minimum and maximum discharge of 87 and 212 cfs, respectively (Osburn, 2007).

The relationship between the current velocity and manual discharge measurements of Blue Spring is graphically illustrated in Figure 4 (Osburn, 2007). The measurement station was destroyed by a hurricane on September 8, 2004, and was not repaired until March 21, 2005. As illustrated in Figure 4, there is a discrepancy between the current velocity measurements (blue line) and the manual measurements (pink triangles). Current velocity discharge data for the period January 1, 2005, through March 31, 2005, were used to represent Blue Spring discharge rates in this analysis (Figure 4). As illustrated, the data are consistent in general trend, although the manual data appear to be slightly higher than the current velocity measurements. The manual measurements are reported to have less uncertainty than the current velocity measurements (S. Williams, personal communication). The manual data help fill in the data gap in current velocity discharge data.

9. Volusia County Groundwater Flow Model

9.1 MODFLOW Model

The MODFLOW-DCM model was constructed using the Volusia MODFLOW model (Williams, 2006) as a template. The Williams Volusia model domain encompassed most of Volusia County with the exception of a small segment located southeast of Lake Hamey, and it includes small parts of Brevard, Seminole, Orange, Lake, Putnam, and Flagler Counties. The model domain was discretized into 100 columns and 100 rows of uniform size (2,500 feet × 2,500 feet) for a total of 10,000 elements. The Williams (2006) model had three layers to represent the surficial aquifer system, the Upper Floridan Aquifer, and the Lower Floridan Aquifers and two intervening confining units to represent the intermediate confining unit (separating the surficial and Upper Floridan Aquifer) and the middle semiconfining unit (separating the Upper Floridan Aquifer from the Lower Floridan Aquifer). The aquifer layers in the Williams (2006) model were explicitly defined by elevation. The confining layers were defined by nonuniform leakance terms. The top of the surficial aquifer was defined by groundwater elevation, which is computed by the model. The elevation of the base of the Upper Floridan Aquifer was adapted from Miller (1986) and modified by McGurk et al. (1998) (Williams, 2006). Williams (2006) modified the base elevation of the Upper Floridan Aquifer during model calibration. The base of the surficial aquifer was defined as the first occurrence of either an identifiable confining layer or the top of the Upper Floridan Aquifer (Williams, 2006).

Williams (2006) employed several types of boundary conditions. Specified head was assigned to large water bodies including lakes greater than 500 acres, the Indian River Lagoon, and the Atlantic Ocean. Lakes greater than 500 acres included Crescent Lake, Lake George, Lake Monroe, Lake Jesup, Lake Harney, and the Intracoastal Waterway. Head-dependent flux conditions were assigned to rivers. A modified form of the head-dependent flux condition was used to simulate flow to subterranean springs. Specified flux was assigned to pumpage by wells and simulated recharge to the surficial aquifer. Wells in the Williams model extracted water from both the surficial aquifer and the Upper Floridan Aquifer. A no-flow condition was assigned to the base of the model (i.e., the base of the Lower Floridan Aquifer). During calibration, Williams (2006) modified the base boundary condition to be head-dependent to assess the potential hydraulic exchange between fresh and saline waters.

Williams (2006) derived initial conditions and property values based on previous groundwater model assessments. The Williams (2006) model had eight categories of hydraulic conductivity assigned to the Upper Floridan Aquifer. The categories ranged from a low of 20 to 40 feet/day for a corridor in the northwest section of the modeled area to a high of 2,500 to 6,400 feet/day for the area closest to the region containing Blue Spring and an area to the east of Blue Spring. Recharge to the surficial aquifer was determined using precipitation, topographic elevations, evapotranspiration, and the estimation of depth to water.

9.2 MODFLOW-DCM Model Adaptations

MODFLOW-DCM Version 2.0 (Painter et al., 2007) can accommodate conduit flow, but is limited to a single hydrostratigraphic layer, albeit one with a conduit network embedded in a diffuse continuum. The mathematical formulation and input instructions for MODFLOW-DCM (Painter et al., 2007) are described in Appendices A and B. The base of the model domain of the MODFLOW-DCM model assembled for Volusia County was designated as the base of the Upper Floridan Aquifer (Figure 5) with the top defined by the ground surface elevation (Figure 6). Boundary conditions were taken directly from Williams (2006), including the Williams (2006) designation of the surface water bodies as constant-head boundaries.

Wells and pump rates from the Williams (2006) model were included in the MODFLOW-DCM model. There were a total of 5,577 wells included in the Williams (2006) model. Of these, 2,254 were identified as wells within water-supply systems and 3,323 wells as domestic. All water-supply system wells were deemed to be in the Upper Floridan Aquifer (Williams, 2006). Domestic wells were assumed by Williams (2006) to extract half of their pumpage from the surficial aquifer and half from the Upper Floridan Aquifer. Domestic wells were modified in the MODFLOW-DCM such that all pumpage was from the Upper Floridan Aquifer.

There were 674 elements designated as river elements in the Williams MODFLOW model (Williams, 2006). All river elements in the Williams (2006) model were set in the surficial aquifer. These 674 river elements were modified and set in the Upper Floridan Aquifer in the MODFLOW-DCM model.

There were a total of 816 elements designated as general head boundary elements in the three layers of the Williams MODFLOW model (Williams, 2006). They were designated in all three layers along the western and southern model boundaries and in the interior of the Lower Floridan Aquifer layer at the 5,000 ppm chloride isochlor. Two modifications of the general head boundary were evaluated: one in which the western and southern boundaries were assigned properties from the surficial aquifer in Williams model and one in which the western and southern boundaries were assigned properties from the Upper Floridan Aquifer. General head boundary conditions from the Lower Floridan Aquifer were not incorporated into the MODFLOW-DCM model. Simulation results in terms of spring discharge and head values at the three target wells were insensitive to the choice of general head boundary condition data set.

9.3 MODFLOW-DCM Basecase Model

A set of properties was identified for the MODFLOW-DCM basecase model. This data set was representative of property values in Williams (2006), but may not represent the best model in terms of agreement with model target criteria used in this analysis. Following are descriptions of the properties assigned to the MODFLOW-DCM basecase model. The eight hydraulic conductivity zones assigned to the Upper Floridan Aquifer in the Williams (2006) model were reduced to seven zones in the MODFLOW-DCM model by combining the two most permeable zones in the Williams model (i.e., 1,280 to 2,560 and 2,560 to 6,400 feet/day) into one zone in the MODFLOW-DCM model. The values assigned to the seven zones of diffuse-layer hydraulic conductivity in the MODFLOW-DCM basecase model were 30, 60, 120, 240, 480, 960, and 1,920 feet/day. These values were taken as the midvalues from the range of values as characterized in the Williams (2006) model. The distribution of the eight conductivity zones is illustrated in Figure 7.

The conduit network of the basecase was established with a depth of 150 feet with ground surface specified for the top elevation and 150 feet below the ground surface as the base elevation. The conductivity of the conduit network was uniform at 2.0×10^{7} feet/day. The conduit-diffuse exchange term was maintained at 1.0 in all simulations. This value is consistent with previous MODFLOW-DCM simulations of the Upper Floridan Aquifer (Painter et al., 2007). The specific storage and specific yield were 1.0×10^{-5} and 0.01 for the conduit network and 3.0×10^{-5} and 0.05 for the diffuse layer, respectively.

9.3.1 Conduit Location

A conduit network is believed to discharge at Blue Spring. The location and extent of this network are not known. Lack of definition of the extent of the springshed of Blue Spring increases the difficulty of defining the location and extent of conduits. Several lines of evidence, either direct or indirect, have been used to ascertain the possible, if not probable, location and extent of the network. Direct evidence of conduit location is typically provided by dye tracer tests or cave mapping by divers. There is no known evidence of tracer tests or cave mapping available for the Blue Spring conduit network.

Worthington and Ford (1995) and Worthington (1999, 2003) provide a number of additional physical indicators that have been used to imply the location of conduits. These are summarized as the following:

- Correlating dolines with the upgradient ends of conduits
- Combining core, packer, slug, and aquifer tests to identify scaling effects of a conduit network (Kiraly, 1975)
- Conducting variable rate pump tests. Pump tests performed near conduits are hypothesized to exhibit a nonlinear pumping rate – drawdown response (Hickey, 1984)
- Conducting matrix and fracture packer test to calculate fracture extent (Price, 1994)
- Observing a lack of symmetry of cones of depression at pumping wells located near conduits
- Continuously monitoring water-levels

- Monitoring water-quality following rainfall to detect rapid response in water chemistry

- Observing troughs in the water table. The combination of high permeability in channels and tributary flow to conduits results in lower hydraulic heads near conduits (Quinlan and Ray, 1981)

- Observing decreasing hydraulic gradients in the downflow direction (Quinlan and Ray, 1981)

- Using environmental isotopes to characterize groundwater age distribution. In a porous medium, water age increases with depth. In a medium with conduits, younger water near a conduit will underlie older diffuse water.

Attempts have been made to use these indicators to identify conduit locations in the springshed of Blue Spring. The distribution of closed topographic depressions near Blue Spring indicated dolines (Figure 8). As illustrated, doline distribution is pervasive in the area mapped. No clear trend, either areally or linearly, is apparent in the closed topographic depression map.

Geologic lineaments have been used to locate karstic features (Beatty and Spangler, 1978; Wood, 2003; Florea and Vacher, 2004). Excessive sediment coverage over much of the study site and lack of coherent trends in areas where the Upper Floridan Aquifer is exposed at the surface rendered this approach an unsuccessful tool to discern conduit locations in the springshed of Blue Spring.

Depressions in the potentiometric surface (i.e., groundwater troughs) of the Upper Floridan Aquifer indicated possible conduit location (Worthington and Ford, 1995; Worthington, 1999, 2003). A distinct groundwater trough terminates immediately east of Blue Spring (Figure 9). It is aligned with and about three miles east of the St. Johns River (Figure 9). This trough continues to the north, past Ponce de Leon Springs. It is not anticipated that a single conduit network links both spring systems. It is possible that karst development of a conduit near St. Johns River evolved in concert with the river or that paleokarst development occurred beneath and/or adjacent to the current floodplain during times of much lower sea level corresponding to previous glacial maxima. This could have resulted in buried karst structures along the St Johns River floodplain. Similar development was hypothesized in the Barton Springs segment of the Edwards Aquifer (Painter et al., 2007). If this is accurate, direct recharge of this conduit is believed to be limited because of the extensive low permeable sediments in the floodplain. The DeLand Ridge has extensive karst development as exhibited by the highly developed karst landforms at the surface and the relative absence of surface water features such as rivers or lakes.

Water-elevation responses at wells are another indicator used in conduit location identification and characterization. High temporal resolution data from select wells have been analyzed to discern whether the signature responses provide insight into conduits. Panagopoulos and Lambrakis (2006) used a combination of techniques, including autocorrelation, spectral density, and crosscorrelation, to differentiate a slightly karsified system from a well-developed karst system. Massei et al. (2006) used wavelet analysis to extract high-frequency responses associated with rainfall from low-frequency responses associated with delayed-infiltration phenomena. The delayed response acted similar to a response expected from epikarst.

Padilla and Pulido-Bosch (1995) performed correlation and cross-spectral analyses of rainfall and spring hydrograph data for four sites of similar size, but different karst development. Their analyses were capable of parsing out quickflow, intermediate flow, and baseflow from the hydrograph. Yu and Hatfield (2007) extended and applied this approach to the Blue Spring system. Spectral and cross-correlation analyses of rainfall-groundwater elevation data and groundwater elevation data-spring discharge provided insight into the hydraulic relationship between the select wells and the conduit system at Blue Spring (Yu and Hatfield, 2007). Yu and Hatfield (2007) analyzed high-resolution well responses at four wells: V-1091, V-0867, V-0083, and V-0059 (Figure 10). Cross-correlation analysis with rainfall suggested response times of 74, 74, 45, and 32 days, respectively. Spectral analysis indicated harmonic lag times of 21, 39, and 83 days at V-1091 and a lag (i.e., aquifer response) of 86 days at well V-0867. The maximum correlation coefficient between rainfall and groundwater elevations was only 0.22.

Better correlations were discerned between groundwater elevations and discharge at Blue Spring. Correlation coefficients using groundwater elevation data collected daily for the same wells and discharge at Blue Spring ranged from 0.46 to 0.77. The response times for the well located at Blue Spring, V-0083, were 4 and 24 days. The aquifer response for well V-1091, located 1.5 miles south of Blue Spring, was 29 to 30 days. Conversely, the aquifer response for well V-0867, which is located about 4 miles northeast of Blue Spring, was only 14 to 16 days. Well V-0059, located 5.5 miles northwest of Blue Spring, had a response time of 27 days. Cross-correlation analysis using hourly data for the same wells indicated comparable aquifer response times.

Aquifer-response times from the Yu and Hatfield (2007) analyses indicated the relative hydraulic connection between the wells and Blue Spring. The relatively long response time of well V-1091 compared to the shorter response time of well V-0867 indicates that V-1091 is not proximal to the conduit network that discharges at Blue Spring. Well V-0059 has a response time (i.e., 27 days) similar to V-1091 (i.e., 29-30 days), even though V-0059 is almost four times as far from Blue Spring. This suggests that V-0059 is closer to the conduit system than V-1091, but not as close as V-0867 is to the conduit network.

The conduit network for the MODFLOW-DCM basecase model was developed incrementally to honor this guiding information. The network was initially developed as a single conduit that roughly paralleled the groundwater trough located north of Blue Spring. Additional segments of conduit were incrementally added to the network to ascertain the extent of the springshed of Blue Spring. These segments extend into the DeLand Ridge and west across the St. Johns River to connect with the area of high recharge located in the southwest of the study area. Williams (2006) previous analyses indicated Blue Spring is recharged from this area. The conduit network used in the MODFLOW-DCM basecase model is illustrated in Figure 11. This network was incorporated in all model simulations reported in this document.

9.3.2 Recharge Distributions

Assessment of recharge of the Upper Floridan Aquifer, as discussed in Section 8.1, is challenging under the best of circumstances. The difficulty in this challenge is increased when components integral to recharge (i.e., soil depth, evapotranspiration, precipitation, etc.) and the effect of the surficial aquifer are consolidated into a single-layer numerical model. The objective in this assessment is to accurately represent the rates at which the Upper Floridan Aquifer is recharged instead of attempting to represent the physical mechanisms that lead to recharge.

Two distinctly different conceptualizations of recharge were considered in these analyses. A different distribution was assigned to each conceptualization. The first distribution (No. 1) is correlated with the base of the surficial aquifer as defined in the Volusia County model (Williams, 2006) (Figure 12). The justification for this representation of recharge is that recharge would be greater in areas where the base of the surficial aquifer has higher elevation. Areas where the base of the surficial aquifer is lower are thought to have (i) thicker sediments which would impede infiltration and (ii) lower hydraulic heads in the surficial aquifer. Both of these factors are believed to decrease recharge to the Upper Floridan Aquifer.

The second distribution (No. 2) closely reflects the topography of the four ridges in Volusia County (Williams, 2006). Recharge is greatest in areas where the Upper Floridan Aquifer is exposed, where relatively highly permeable overburden sediments are present, or in the presence of karst features such as sinkholes. The Upper Floridan Aquifer is not significantly exposed at lower elevations in the study area (Figure 13). Recharge distribution No. 2 was assigned to the basecase.

9.3.3 Basecase Hydraulic Responses

MODFLOW-DCM model simulations occurred over a 15-month period of performance from January 1, 2004, through March 31, 2005. This period was selected because of the availability of spring discharge, precipitation, and well groundwater-elevation data and because it included a period of relatively large precipitation and spring discharge. Daily discharge values for Blue Spring are estimates based on U.S. Geological Survey measurements of current velocity. The Blue Spring measurement station was destroyed during a hurricane on September 8, 2004, and was not repaired until March 21, 2005, causing a gap in data. U.S. Geological Survey has also provided intermittent manual discharge measurements (Osburn, 2007). These are believed to be more accurate than current velocity measurements; however insufficient manual discharge measurements are available for use in model evaluation. SJRWMD (Williams, personal communication) provided daily precipitation data. Daily precipitation recorded at DeLand was summed into 15 monthly periods (Table 4).

Osburn (2007) plotted water elevations for several wells located near Blue Spring (Figure 14). As illustrated in Figure 14, responses among the wells are highly correlated as their recorded water levels indicated. Three of the wells were selected as index wells for comparison with model results: V-0083, V-0867, and V-1091 (Figure 9). These were selected because they all extend into the Upper Floridan Aquifer and each has daily groundwater-elevation data available for most of the 15-month-long period of performance (January 1, 2004, to March 31, 2005).

For the basecase model, results are presented as the potentiometric surface (Figure 15) and in four graphs: discharge at Blue Spring and groundwater elevations at three index wells— V-0083, V-0867, and V-1091 (Figure 16). The basecase groundwater elevation surface (Figure 15) captures the general features of the pre-development potentiometric surface (Figure 9) (i.e., a depression concurrent with St. Johns River and elevated areas associated with the DeLand Ridge and the western boundary), however, there are significant departures between the two surfaces. The principle sources of the differences are attributed to uncertainty in recharge and the possibility that the transmissivity (i.e., hydraulic conductivity and aquifer thickness) assigned to the equivalent continuum representation of the Upper Floridan Aquifer in the Williams (2006) model, may not be appropriate for a dual continuum representation (i..e., conduit network separated from the matrix continuum) in the DCM version of the Volusia County model developed in this study. As discussed in this study, two recharge distributions were considered, however a full reassessment of the hydraulic conductivity representation was not undertaken as part of this evaluation. Significant departures between the pre-development and the basecase potentiometric surfaces may be an indication that a distinctly different assignment of hydraulic characterization may be needed to resolve and reduce these differences.

As illustrated, measured data are not available for the entire period of performance for spring discharge and well V-0083. Baseflow discharge at Blue Spring in the basecase model was less than observed; however, simulated spring discharge during the high precipitation event was earlier and possibly greater than observed values. Model groundwater elevations at V-0867 and V-0083 were greater and less responsive than observed; however, groundwater elevations at V-1091 were less than observed values, but with the appropriate level and timing of responsiveness. Annual recharge for the basecase model equated to 5.77 inches/year when uniformly averaged over the entire model area (i.e., 250,000 feet × 250,000 feet).

9.4 Sensitivity Analyses

A variety of changes to the MODFLOW-DCM model was made to evaluate the effect of property assignment and boundary conditions on the model simulation. The following model input values were varied during the sensitivity analyses:

- Recharge distribution

- Recharge values
- Diffuse hydraulic conductivity
- Conduit hydraulic conductivity
- Storativity and storage coefficient
- General head boundary
- Well elements
- River elements
- Conduit network extent

In addition to these sensitivity analyses, the way in which the Williams (2006) three-layer MODFLOW general head boundary conditions, river conditions, and well elements were incorporated into the one-layer MODFLOW-DCM mode was evaluated. This evaluation process and the ultimate model property selection were described in the section describing model properties. Evaluation of the well elements, river elements, general head boundaries, and the conduit network were reported in previous sections. Notable model results are discussed in the following sections.

9.4.1 Recharge Distributions

The basal elevation of the surficial aquifer was selected as an alternative recharge distribution. This surface was selected in an attempt to incorporate the cumulative effect of precipitation, evapotranspiration, and epikarst on recharge. The effect of the more uniformly distributed recharge (Figure 12) on model performance was to decrease spring discharge when compared with the model with recharge focused over the DeLand Ridge area (Figure 13). Because of the modified distribution, different absolute parameter values were assigned to recharge values to insure that cumulative recharge quantities were reasonable; however, their relative values were maintained apportionate to approximate annual precipitation rates. The annual average uniform recharge rate was 4.46 inches/year. Spring discharge and groundwater elevations for the three index wells are plotted in Figure 17 for this recharge distribution. Having more uniformly distributed recharge decreased both the baseflow and peak flow spring discharge. There were minimal changes in predicted heads at V-0867 and V-0083, but some improvement in the predicted head at V-1091.

9.4.2 Recharge Values

In general, increasing the recharge values significantly increased both discharge at Blue Spring and diffuse-layer head values. In this simulation, recharge was doubled relative to the basecase model. The average annual uniform recharge was increased to 11.55 inches/year. There were minimal changes in predicted heads at V-0867 and V-0083, but some improvement in the predicted head at V-1091. The resulting spring discharge and groundwater elevations for the three index wells are illustrated in Figure 18.

9.4.3 Diffuse Hydraulic Conductivity

A range of hydraulic conductivity values was evaluated during the sensitivity analyses. In general, increasing the hydraulic conductivity values assigned to the diffuse layer resulted in lower head values at the three index wells. Increasing the diffuse-layer hydraulic conductivity allowed greater recharge values required to achieve better agreement in spring discharge while keeping head values in the diffuse layer lower and closer to the observed values. The diffuse-layer hydraulic conductivity values required to achieve this balance, however, exceeded values considered representative of the Upper Floridan Aquifer. Regardless, results from this simulation indicate that further adjustment of the diffuse-layer hydraulic conductivity values could lead to better agreement with observed head values. The resulting spring discharge and groundwater elevations for the three index wells with diffuse-layer conductivity values were increased by a factor of 10 relative to the basecase model values (Figure 19). As illustrated in the figure, an increase in the diffuse layer hydraulic conductivity resulted in improved model performance. In fact, this simulation provided the closest match with the target criteria compared with all test cases.

9.4.4 Conduit Hydraulic Conductivity

The hydraulic conductivity of the conduit network was doubled from 2.0×10^7 to 4.0×10^7 feet/day. All conduit elements were uniformly varied during this analysis. Increasing the conduit conductivity by a factor of two increased both Blue Spring baseflow and peak flow. The baseflow for this model is close to the observed baseflow, but peak flow was probably unrealistically high; however, this is not known with certainty in the absence of measured discharge. Head values at the three index wells were not changed significantly from the basecase model results. The resulting spring discharge and water levels for the three index wells for the basecase model with conduit conductivity increased from 2.0×10^7 to 4.0×10^7 feet/day (Figure 20).

9.4.5 Storativity and Storage Coefficient

The specific yield of 0.05 for the diffuse layer and 0.01 for the conduit network were reduced by a factor of 10. This increased Blue Spring baseflow to close to the observed baseflow, but increased peak flow to excessive rates (Figure 21). Diffuse-layer heads were more responsive with a slight improvement in overall groundwater elevation values.

9.5 Model Performance

The performance of the MODFLOW-DCM model of Volusia County is evaluated in terms of transient discharge at Blue Spring and groundwater elevations at three local index wells.

9.5.1 Blue Spring Discharge

Spring discharge baseflow rates are approximately 150 cfs during the period of performance used in this analysis (i.e., January 1, 2004, through March 31, 2005). Blue Spring baseflow discharge was marginally underpredicted (i.e., discharge ~ 90 cfs) in the basecase simulation. Simulated spring baseflow approximated the observed baseflow when the overall recharge rate or the conduit conductivity was doubled; however, in both cases peak spring flow was increased to unrealistically high rates (i.e., 500 to 600 cfs).

The conduit network of the Volusia County MODFLOW-DCM model only incorporated Blue Spring. The effects of conduit flow to the other significant springs in the model domain were not incorporated. Although Blue Spring is the largest spring in the model domain, other springs are significant (Table 3). Their combined effect could be important to model performance.

9.5.2 Index-Well Groundwater Elevation Values

The domain for the Volusia County MODFLOW-DCM model spanned 250,000 feet × 250,000 feet, although model performance was evaluated using three index wells located no farther than 25,000 feet from Blue Spring. Comparison of model performance at index wells farther from Blue Spring could provide insight on the extent of the springsheds of Blue Spring and other springs in the model domain.

The groundwater elevations predicted at well V-1091 were frequently lower than measured values, although similar predicted values at V-0083 and V-0867 were higher. None of the three index wells is near boundaries that could otherwise be a source of this discrepancy. Local property assignment effects on index well-water head values were evaluated by varying the hydraulic conductivity assigned to the diffuse layer near Blue Spring and the index wells. These simulations did not resolve the relative discrepancy in groundwater elevations among the three wells.

9.5.3 Hydraulic Lag

The observed hydraulic lag between recharge events and spring discharge (Yu and Hatfield, 2007) was greater than the Volusia County MODFLOW-DCM model predicted. This may be attributed to the manner in which recharge, evapotranspiration, and infiltration through the epikarst were incorporated into a simple recharge value. The observed hydraulic lag between recharge and water level responses at index wells (Yu and Hatfield, 2007) was close to that the Volusia County MODFLOW-DCM model predicted. This discrepancy in responsiveness between spring discharge and index well groundwater elevations may indicate the greater effect of diffuse-layer flow on index wells' water levels than conduit flow spring discharge.

10. Conclusions

The standard MODFLOW model for Volusia County by Williams (2006) was converted into a dual continuum model in an attempt to account for both the slow diffuse flow and the rapid conduit flow the Floridan Aquifer exhibited. Capturing both flow regimes in groundwater flow models is important to replicating the dynamic response of Blue Spring to recharge and pumping. The dual continuum model MODFLOW-DCM Version 2.0 (Painter et al., 2007) was used in the simulations.

Similar to development of a MODFLOW-DCM model for the Santa Fe system in northwest Florida, recharge proved to be a critical model input factor (Painter et al., 2007). Simulation of the Santa Fe system and review of the technical literature suggests that recharge rates of approximately 18 inches/year are appropriate for areas with minimal overburden overlying the Upper Floridan Aquifer and 2 inches/year for areas with significant overburden or in areas where the Upper Floridan Aquifer is confined. This suggests that recharge rates of 5 to 10 inches/year, when averaged for the entire model domain, are reasonable.

The MODFLOW-DCM version of the Volusia County groundwater model was constructed with a conduit network embedded in a diffuse layer to capture the flow system that discharges at Blue Spring. Data available for evaluating the model included groundwater elevation measurements taken at three index wells and discharge measurements at Blue Spring. Measurements at the index wells are believed to be sufficiently accurate, but all three index wells are near Blue Spring and there were no well data from other regions of the model domain to indicate how the aquifer responds in those areas to changes in recharge and pumping. Uncertainty in discharge rates from Blue Spring resulted from incomplete records of discharge for the target period of performance.

The redefined conduit/diffuse layer model replicated the dynamic response of spring discharge and groundwater elevations to seasonal changes in precipitation, but the transient model was not calibrated. The MODFLOW-DCM model approximately replicated the Blue Spring discharge hydrograph during high recharge events, although baseflow discharge and the lag between rainfall and discharge were not successfully reflected in the model simulations. Baseflow discharge at Blue Spring was underpredicted by about 40 percent in the basecase simulation. Replication of groundwater elevations at an index well near Blue Spring and an index well in the DeLand Ridge, which is within the suspected area of recharge for Blue Spring, was more successful than replication of groundwater elevations in an area south of Blue Spring, which is not believed to be a significant area of recharge for Blue Spring. Groundwater elevations at the Blue Spring and DeLand wells were generally overpredicted, while heads at the well to the south of Blue Spring were underpredicted. These discrepancies indicate that model conduit locations relative to the wells or the hydraulic conductivity values assigned to the diffuse layer need modification.

Sensitivity analysis results highlighted the relative effects that changes in conduit conductivity, diffuse layer hydraulic conductivity, recharge distribution and intensity, and storage coefficient have on model performance. An increase in the diffuse layer hydraulic conductivity relative to the basecase provided the best performance in terms of matching the target criteria. In general, the MODFLOW-DCM version of the Volusia County groundwater flow model proved to be responsive to these changes in property value assignments and boundary conditions; however, target hydraulic head data at additional locations in the model domain and a more complete record of spring discharge would be beneficial, if not required, to effectively calibrate the transient model.

11. Recommendations

Although fundamental flow components to the conduit-diffuse flow system at Blue Spring were replicated in this study using MODFLOW-DCM, the current version of the Volusia County dual continuum model is not sufficiently refined to be of use in water resource management. Additional tasks to improve the model have been identified. Difficulties were encountered when attempting to calibrate a transient dual continuum model of Volusia County. The root cause of this difficulty was, at least in part, due to an inadequate data set that represents the physical system. Data available for this analysis included groundwater elevation measurements taken at three index wells within 5.5 miles of Blue Spring and automatically recorded discharge measurements at Blue Spring. Measurements at the index wells are believed to be sufficiently accurate, but all three index wells are near Blue Spring and there were no well data from other regions of the model domain to indicate how the aquifer responds in those areas to changes in recharge and pumping. Groundwater elevation measurements from index wells in other parts of the model domain should be incorporated in the analysis to evaluate model performance.

Discharge for Blue Spring estimated using current velocity measurements is less accurate when compared with manual measurements (Osburn, 2007); however, this discrepancy is minor when compared with the larger discrepancy between baseflow the dual continuum model predicted and the observed values. Williams (personal communication) noted that the manual measurements are more accurate than estimates made using current velocity measurements. Nonetheless, this discrepancy should be resolved to minimize uncertainty in future aquifer simulation efforts.

The nature and extent of the conduit network in the dual continuum model should be enhanced. During this evaluation, the conduit network was expanded in a piecemeal fashion to test model performance response to increased springshed size. The effect of expanding the conduit network to include more of the DeLand ridge recharge zone should be evaluated. Conduit networks should be added for the other major springs in the model domain. A more representative conduit network can be predicated using mapped cave geometries of other conduit systems in the Floridan Aquifer in north-central and northeast Florida. An additional analytical tool would be to apply geomorphological and hierarchical analysis techniques developed for surface rivers and streams to identification of a subsurface conduit network (Rodriguez-Iturbe and Valdes, 1979).

The effect of epikarst and the relative large size of the recharge (springshed) zone should be examined. It is likely that the epikarst has a hydraulic effect on the lag observed in spring discharge and groundwater elevations observed at the index wells. There is a challenge in this recommendation because the dual continuum conceptualization in MODLFOW-DCM is limited to a single-layer model. It may be necessary to account for the effect of delayed flow through the epikarst by *a priori* adding a delay in the timing of recharge. Correlation analysis among spring discharge, groundwater elevation, and precipitation should be expanded to include wells and springs over a larger geographical area. Correct replication of hydraulic lag in spring discharge may be resolved when the conduit network is modified to account for the full extent of the springshed.

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Table 1. Summary of estimated ranges of water budget components for the surficial aquifer system (inches/year) (Williams, 2006)

Component	Lowlands	Terraces	Eastern Ridges	Western Ridges
Evapotranspiration	42-46	36-42	30-36	27-30
Runoff	4-8	0-8	8-12	0-6
Recharge	0-4	4-8	8-10	10-18

Table 2. Stratigraphic and hydrostratigraphic units of the northern Florida

<table>
<tr><th>Series</th><th>Stratigraphic Unit</th><th colspan="2">Hydrostratigraphic Unit</th><th>Lithology</th><th>Thickness (m)</th></tr>
<tr><td>Holocene
Pleistocene
Pliocene</td><td>Undifferentiated sediments</td><td colspan="2">surficial aquifer</td><td>fine sands and gravel</td><td>0-25</td></tr>
<tr><td>Pliocene to Miocene</td><td rowspan="2">Hawthorn Group sediments</td><td colspan="2" rowspan="2">intermediate aquifer/confining bed</td><td rowspan="2">interbedded sands and clays carbonates</td><td rowspan="2">0-45</td></tr>
<tr><td>Miocene</td></tr>
<tr><td>Oligocene</td><td>Suwannee Limestone</td><td rowspan="3">Floridan Aquifer System</td><td rowspan="2">Upper Floridan Aquifer</td><td rowspan="3">porous limestone and dolomite</td><td rowspan="3">325-425</td></tr>
<tr><td rowspan="2">Eocene</td><td rowspan="2">Ocala, Avon Park, and Oldsmar Formations</td></tr>
<tr><td>LFA</td></tr>
<tr><td>Paleocene</td><td>Cedar Keys Formation</td><td colspan="2">sub-Floridan Confining Unit</td><td>limestone with some clay and evaporites</td><td>?</td></tr>
</table>

Table 3. Summary of springs in the Volusia County model domain (Williams, 2006)

Spring	Estimated Predevelopment Flow (cfs)	Average Measured Flow (cfs)
Blue	160	150
Rock	70	61
Seminole	40	39
Ponce de Leon	31	27
Messant	20	16
Gemini	10	8
Island	10	6
Green	1	2
Camp La No Che	1	1
Sulphur	2	1
Doty	1	1

Table 4. Monthly precipitation values for January 1, 2004, through March 31, 2005 (inches)

Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
1.1	3.77	1.85	3.51	2.78	6.8	9.5	21.55	18.11	1.42	1.71	2.88
Jan	Feb	Mar									
2.5	1.77	4.46									

APPENDIX A: MODFLOW-DCM VERSION 2.0
(Painter et al., 2007)

DCM Version 1.0, a dual-conductivity module for MODFLOW, was developed in Phase I of the karst modeling project. Version 1.0 was implemented as a self-contained module ("package" in the MODFLOW terminology). Numerical experiments undertaken as part of Phase I revealed poor numerical performance and even convergence failures for DCM Version 1.0. The numerical performance issue was resolved during the current phase of the project by adding a new solver for MODFLOW. The new solver, NR1, is based on the Newton-Raphson method and requires derivative information from active MODFLOW packages. Because of this new data requirement from the packages, NR1 could not be implemented as a self-contained package and it was necessary to modify multiple packages. The result is a new MODFLOW variant denoted MODFLOW-DCM Version 2.0.

Input for MODFLOW-DCM follows the standard MODFLOW formats. To use MODFLOW-DCM, the user must specify the DCM groundwater flow package in the name file. Other groundwater flow packages (BCF, LPF, etc.) must not be specified. Required inputs for the DCM groundwater flow packages include conduit and diffuse system parameters, a matrix/conduit exchange parameter, and optionally, one parameter required for the turbulence model. Conduits are defined by activating relevant MODFLOW cells and assigning hydraulic conductivity and storage parameters to each conduit cell. The NR1 solver is automatically activated. The user must not activate other solver packages.

Note that MODFLOW-DCM Version 2.0 is currently limited to single-layer aquifers. Thus, the software will model the situation shown in Figure A.1(a), but not the multilevel configuration shown in Figure A.1(b). To model the configuration shown in Figure A.1(b) or an aquifer with multiple layers with disparate properties [Figure A.1(c)], a three-dimensional version of MODFLOW-DCM would be required.

This appendix summarizes the technical basis for MODFLOW-DCM Version 2.0. A review of the groundwater flow representation in MODFLOW is provided first. Subsequent sections describe the dual-conductivity representation, conduit flow model, simulation of dry cells, basis for the new solver, and software validation activities. Input formats for the DCM package and NR1 solver are provided in Appendix B.

Groundwater Flow Representation in MODFLOW

In MODFLOW, flow is conceptualized as occurring in an aquifer with multiple layers that may be stacked one upon the other. For a single layer using principal coordinates, the groundwater flow equations can be written

$$S(h)\frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left[T_x(h)\frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial y}\left[T_y(h)\frac{\partial h}{\partial y}\right] + Q \qquad h \in \Omega \tag{A-1}$$

where h [L] is hydraulic head, T_x (T_y) [L^2] is transmissivity in the x (y) direction, S [unitless] is a storage term, and Q [L/T] is the volumetric source term per unit area of the aquifer. Equation (A-1) applies for both confined and unconfined aquifers with appropriate definitions of the head-dependent parameters T and S. Specifically, let $Z^{top}(x,y)$ denote the elevation of the top of the aquifer and $Z^{bot}(x,y)$ the bottom elevation. The x-direction transmissivity is then written

$$\begin{aligned} T_x &= 0 && h \le Z^{bot} \\ T_x &= K_x\left(h - Z^{bot}\right) && Z^{bot} < h < Z^{top} \\ T_x &= K_x\left(Z^{top} - Z^{bot}\right) && h \ge Z^{top} \end{aligned} \qquad \text{(A-2)}$$

where K_x [L/T] is the x-direction hydraulic conductivity. The y-direction transmissivity is written similarly. For the storage term, the corresponding equation is

$$\begin{aligned} S &= 0 && h \le Z^{bot} \\ S &= S_Y && Z^{bot} < h < Z^{top} \\ S &= S_S\left(Z^{top} - Z^{bot}\right) && h \ge Z^{top} \end{aligned} \qquad \text{(A-3)}$$

where S_Y [unitless] is the specific yield and S_S [L^{-1}] is the specific storage.

Dual-Conductivity Model

In the conventional MODFLOW software, Equation (A-1) is solved over a specified region, Ω. For the dual-conductivity model, it is necessary to keep track of two hydraulic heads: one for the conduit and one for the diffuse system. Hydraulic head in the diffuse system is defined over the entire region, Ω, as in the single conductivity case. The conduit hydraulic head is defined only for those spatial locations that correspond to a conduit. To be more specific, consider a system of n conduits, and let Ψ_i denote the spatial region occupied by the i^{th} conduit. Let the subscript c denote the conduit system, so that the hydraulic head of the conduit system becomes h_c. Similarly, let a subscript m denote the diffuse, or matrix, system. The flow equations then become

$$S_m(h_m)\frac{\partial h_m}{\partial t} = \frac{\partial}{\partial x}\left[T_{mx}(h_m)\frac{\partial h_m}{\partial x}\right] + \frac{\partial}{\partial y}\left[T_{my}(h_m)\frac{\partial h_m}{\partial y}\right] + Q_m + \alpha(h_c, h_m)\left[h_c - h_m\right] \qquad h_m \in \Omega \qquad \text{(A-4a)}$$

$$S_c(h_c)\frac{\partial h_c}{\partial t} = -\frac{\partial}{\partial x}\left[q_{cx}\right] - \frac{\partial}{\partial y}\left[q_{cy}\right] + Q_c - \alpha(h_c, h_m)\left[h_c - h_m\right] \qquad h_c \in \Psi \qquad \text{(A-4b)}$$

where Ψ is the entire region occupied by all conduits $\Psi = \Psi_1 \cup \Psi_2 \cup \Psi_3 \cdots \cup \Psi_n$. Note that while h_m is defined for the entire spatial region, Ω, h_c is defined only for region

Ψ, which is a subset of Ω. If Ω and Ψ correspond, the system of Equations (A-4a,b) is the dual-continuum model that is widely used in fractured rock modeling. For karst systems, the conduit network is generally not well represented as a continuum at the scale of interest, and the system of Equations (A-4a,b) represents a sparse network of conduits coupled to a continuum diffuse system. The transmissivity and storage terms in Equations (A-4a,b) are defined as in Equations (A-2) and (A-3), except that distinct top and bottom elevations may be used for the two flow systems: $Z_c^{top} \leq Z_m^{top}$ and $Z_c^{bot} \geq Z_m^{bot}$. The conduit flow terms q_{cx} and q_{cy} have been left in symbolic form in Equations (A-4a,b). These terms are defined in the next section of this report.

The final term in each equation in Equations (A-4a,b) represents the movement of fluid between the two systems, with α quantifying the strength of the linear exchange. If α is 0, the conduit and diffuse systems decouple, and flow in each system is independent. If the conduit is filled with water, α is simply a number, independent of the head. If the conduit is only partially filled, this value needs to be decreased because only a fraction of the conduit surface area is available to transmit water. Thus, to model unconfined aquifers, α should be dependent on the hydraulic head. The situation is further complicated because flow can be either from the conduit to the diffuse or vice versa, and the surface area available to transmit water depends on the flow direction. The simplest condition incorporating all of these constraints is the linear upwind or upstream condition

$$\alpha = \alpha_0 \left[\frac{\min\left(Z_c^{top}, \max\left(h_m, h_c, Z_c^{bot}\right)\right) - Z_c^{bot}}{Z_c^{top} - Z_c^{bot}} \right] \qquad \text{(A-5)}$$

The term in brackets is unity if the conduit is completely filled with water and zero if both the conduit head and the diffuse head drop below the conduit base elevation. The parameter α_0 [T^{-1}] is the linear exchange coefficient for a conduit filled with water. It is a property of the conduit and, in general, will be spatially variable. Theoretically, α_0 should be proportional to the product of the conduit surface area and diffuse hydraulic conductivity. In practice, it is a property of the system that is to be determined by calibration.

Conduit Flow Model

In mature karst aquifers, conduit flow is often in the turbulent regime. For example, Halihan et al. (2000) estimate 95 to 99 percent of conduits in the Edwards Aquifer have Reynolds numbers greater than 2,000, which represents the approximate threshold for onset of turbulent behavior. Based on this analysis, all conduits with diameters greater than a few centimeters, which presumably dominate flow, would be in the turbulent regime.

For turbulent flow, the familiar linear relationship between Darcy velocity and hydraulic gradient is not valid and is replaced by a nonlinear flow law. By analogy with flow in engineering systems, the Darcy-Weisbach equation is typically assumed for flow in pipes. The Darcy-Weisbach equation relates the macroscopic head loss, Δh, in a straight section of pipe to the flow velocity

$$\Delta h = ff \frac{L}{D_H} \frac{\bar{v}^2}{2g} \tag{A-6}$$

where L is the length of the pipe, D_H is the mean hydraulic diameter, $\bar{v}$ is the mean velocity in the pipe, g is acceleration due to gravity, and ff is the friction factor. For straight pipes, ff depends on the relative roughness ε of the pipe and on the Reynolds number Re. Graphical representations of this dependence can be found in standard engineering handbooks. For Reynolds numbers greater than about 4,000, the dependencies are also well represented by the implicit Colebrook equation (e.g., Murdoch, 1996).

$$\frac{1}{\sqrt{ff}} = -2\log\left[\frac{\varepsilon}{3.7} + \frac{2.51}{Re\sqrt{ff}}\right] \tag{A-7}$$

Gale (1984) and Halihan *et al*. (2000) used similar Reynolds-number-dependent models for friction factors in natural conduits.

For rough pipes, the friction factor becomes independent of Reynolds number; this appears to be appropriate for conduits that are naturally rough walled.

Springer (2004) pointed out that real conduit passages are rarely well approximated as straight pipes, but instead have bends, constrictions, expansions, and contractions. In engineering systems, the head loss caused by such arrangements of components is usually estimated by summing empirically determined values for each component (e.g., Murdoch, 1996).

$$\Delta h = ff \frac{L}{D_H} \frac{\bar{v}^2}{2g} + C_{bends} \frac{\bar{v}^2}{2g} + C_{ec} \frac{\bar{v}^2}{2g} \tag{A-8}$$

where C_{bends} is an empirically determined coefficient accounting for head loss in all bends, and C_{ec} is a similar coefficient for cross-sectional expansions/contractions. Springer (2004) used detailed conduit geometry, flow-loss coefficients from engineering handbooks, and Equation (A-8) to calculate head losses in a segment of the Buckeye Creek Cave in West Virginia. The model was then used to estimate discharge for a flood with known head loss estimated from high water marks recorded as silt lines. Independent estimates of the discharge were not available for verification.

In most applications, detailed conduit geometry is not available and direct calculation of head losses from conduit geometry is impractical. Instead, a lumped parameter that can be inferred or calibrated to match spring flows is needed. To this end, note each term in Equation (A-8) has identical dependence on velocity. Thus, the effects of the various bends and cross-sectional variations can be grouped into an effective friction factor

$$\Delta h = ff_e \frac{L}{D_H} \frac{\bar{v}^2}{2g} \tag{A-9}$$

An analogous form is more convenient for use in distributed groundwater models

$$q = -\frac{k_c}{\sqrt{\|\nabla h\|}} \nabla h \tag{A-10}$$

where q is the Darcy velocity and k_c is an effective conductivity for the conduit. Jeannin (2001) used this form in modeling flow in the Holloch cave in Muotatal, Switzerland, and calibrated values of k_c to match observed discharges. Jeannin (2001) also converted effective friction factors reported by several authors to an equivalent k_c and showed that conductivity estimates for eight different studies clustered in the range 1-10 m/s.

Equation (A-10) is the preferred equation for modeling turbulent flow in conduits because it concisely accommodates friction and conduit geometry in the hydraulic conductivity term. However, groundwater modeling codes are typically based on the Darcy equation. It should be recognized that a Darcy model can always be calibrated to match a turbulent model in steady state. Specifically, an effective conductivity can be selected as $k_{eff} = k_c \big/ \sqrt{\|\nabla h\|}$, which yields the same flow as the turbulent model in steady state. In transient conditions, however, the hydraulic gradient will necessarily deviate from the value used in calibration, and the two flow models will diverge. Painter *et al*. (2006) used numerical experiments to demonstrate the potential error introduced by applying a Darcy model to karst aquifers with turbulent flow.

The DCM turbulent flow model for conduits can be written

$$q_{cx} = -T_{cx}(h_c) i_{crit}^{1/2} \left| \frac{\partial h_c}{\partial x} \right|^{-1/2} \frac{\partial h_c}{\partial x} \qquad \left| \frac{\partial h_c}{\partial x} \right| > i_{crit} \tag{A-11a}$$

$$q_{cx} = -T_{cx}(h_c) \frac{\partial h_c}{\partial x} \qquad \left| \frac{\partial h_c}{\partial x} \right| \le i_{crit} \tag{A-11b}$$

with analogous expressions for the *y*-components of flux. The parameter i_{crit} is the critical gradient for the onset of turbulence. It is regarded here as a calibration parameter similar to aquifer transmissivity. The turbulent flow equation (Equation A-11a) will be invoked when the hydraulic gradient exceeds the critical gradient i_{crit}, and the laminar flow equation (Equation A-11b) will be invoked when the hydraulic gradient is less than i_{crit}.

Simulation of Dry Cells

When the conventional MODFLOW software calculates a water level that is below the base elevation of a computational cell, that cell is declared to be dry and removed (temporarily or permanently) from the calculation. This dry-cell simulation algorithm may prevent the MODFLOW outer iteration scheme from converging (McDonald *et al.*, 1991). Moreover, if the dry cell has a specified recharge or pumping rate, then making it inactive causes a nonphysical change in the global water balance. These problems with the MODFLOW system are well known and long standing.

A new algorithm to simulate dry cells was developed for DCM Version 1.0 and further refined in MODFLOW-DCM Version 2.0. The algorithm combines a new updating procedure for potentially dry cells with an upstream-weighted calculation of intercell conductances. Upstream weighting uses the saturated thickness in the upstream cell to calculate the intercell conductance for a pair of cells.

In the new updating procedure, the hydraulic head is never allowed to drop below the bottom elevation of a cell. If an outer iteration calculates a hydraulic head that is below the bottom elevation of a cell, the updated head for that cell is set equal to the arithmetic average of the previous head and the cell bottom. This procedure allows the head in a cell to become arbitrarily close to the cell bottom over the course of several iterations. However, the head will always be greater than the cell bottom, thus allowing the cell to remain active in the calculation.

The upstream weighting for the intercell conductance prevents flow from leaving a nearly dry cell while allowing flow to return to a nearly dry cell if the neighboring heads are higher than the cell in question. To express the upstream weighting in a compact form, a simplified, albeit nonstandard, notation is useful. First, suppress the *c* and *m* subscripts; the upstream weighting algorithm applies similarly to both conduit and diffuse system. Let h_{j+} denote the hydraulic head in cell $j+1,i,k$, and let h denote the head in cell j,i,k. Similarly, let CR_+ denote the row conductance between cells j,i,k and $j+1,i,k$. In standard MODFLOW notation, that row conductance is denoted $CR_{j+1/2,i,k}$. In the notation used here, the row conductance is then expressed as

$$CR_+ = CR_+^0 \frac{\min\left(Z_{j+}^{top}, \max\left(h_{j+}, h\right)\right) - Z_{j+}^{bot}}{Z_{j+}^{top} - Z_{j+}^{bot}} \qquad \text{(A-12)}$$

where CR_+^0 is the branch conductance under fully saturated conditions as obtained by harmonic averaging of the hydraulic conductivity. In Equation (A-12), Z_{j+}^{top} and Z_{j+}^{bot} are intercell averages for top and bottom elevations. To prevent flow from leaving a dry cell, the following definition for Z_{j+}^{bot} is needed

$$Z_{j+}^{bot} = \max(Z_{j,i,k}^{bot}, Z_{j+1,i,k}^{bot}) \qquad \text{(A-13)}$$

We have more flexibility in the definition of the Z_{j+}^{top} parameter, and the following is used in MODFLOW-DCM

$$Z_j^{top} = \left(Z_{j,i,k}^{top} + Z_{j,i+1,k}^{top}\right)/\,2 \tag{A-14}$$

With the new handling of dry cells, all initially active cells remain active throughout the simulation. Thus, water balance issues related to drying cells are completely avoided. The algorithm requires no control parameters as input; parameters that controlled rewetting in conventional MODFLOW are not required and are not recognized by the DCM package.

Newton-Raphson Solver

For unconfined aquifers, the groundwater flow equations MODFLOW solved are nonlinear because the branch conductances depend on saturated thickness and thus the dependent variable (hydraulic head). The turbulence model of MODFLOW-DCM introduces additional nonlinearities; with the turbulence model activated, the equations MODFLOW-DCM solved are nonlinear for both unconfined and confined conditions.

The conventional MODFLOW system uses a Picard iteration strategy to resolve the nonlinear terms. With Picard iterations, the branch conductances are calculated using the hydraulic head from the previous iteration. The branch conductances are then held fixed while the head is updated by solving the resulting linear system. This iterative process is repeated until the head changes very little between subsequent iterations. The solution to the linear system itself may also be accomplished by an iterative process. Iterations to solve the linearized system are typically referred to as “inner iterations” and the process of iteratively updating the head and branch conductances as “outer iterations.” All nonproprietary solver packages in the conventional MODFLOW system use a variant on the Picard iteration strategy for the outer iterations.

Picard iteration is generally adequate for mildly nonlinear systems, but may fail to converge or require an excessive number of iterations for more strongly nonlinear systems. Numerical tests with the DCM Version 1.0 package revealed that the large contrast in branch conductances between conduit and diffuse-system cells often leads to convergence failures. In some cases, nearly dry cells also caused convergence failures.

A new Newton-Raphson solver, NR1, was developed for MODFLOW-DCM Version 2.0 to replace the Picard iteration scheme. The Newton-Raphson method for solving nonlinear equations is more robust than the Picard scheme because it uses derivative information in the iterations. The Newton-Raphson method is, however, more difficult to implement than the Picard iteration scheme and requires more information from the groundwater flow packages.

The groundwater flow equations system, discretized with respect to space and time, can be written in symbolic form as

$$\mathbf{R}(\mathbf{h}) = \mathbf{0} \tag{A-15}$$

where $\mathbf{R}$ is the residual vector representing cell-by-cell errors in water balance and $\mathbf{h}$ is the head vector. Let $\mathbf{h}^m$ and $\mathbf{R}^m$ denote the head approximation and resulting residual vector at iteration m. In the Newton-Raphson method, the next iteration of the head is obtained as $\mathbf{h}^{m+1} = \mathbf{h}^{m} + \mathbf{\Delta}^{m}$ where $\mathbf{\Delta}^{m}$ is the solution to the linear system

$$\mathbf{J}^{m}\mathbf{\Delta}^{m} = -\mathbf{R}^{m} \tag{A-16}$$

Here $\mathbf{J}^{m}$ is the Jacobian matrix. The entry J_{pq} in the p^{th} row and q^{th} column of that matrix is the derivative of the p^{th} residual with respect to the q^{th} hydraulic head, $J_{pq} = \dfrac{\partial R_p}{\partial h_q}$.

The NR1 solver implements a slight variation on the classical Newton-Raphson method by employing an adaptive damping strategy. The adaptive damping algorithm is a slight modification to Cooley's method (1983). The algorithm monitors for oscillations in the iteration procedure and applies damping if oscillations are detected.

The linear system given by Equation (A-16) is solved in the NR1 solver by a preconditioned conjugate gradient algorithm. Incomplete lower-upper (ILU) decomposition with a fixed level of fill is used for the preconditioner. Iteration acceleration is by the biconjugate gradient stabilized (BCGSTAB) method. Saad (2003) details the algorithms for solving the linear system.

APPENDIX B: INPUT INSTRUCTIONS FOR THE MODFLOW-DCM PACKAGE (Painter et al., 2007)

B.1 Name File

To activate the DCM package, the following line needs to be added to a MODFLOW name file

DCM Nunit Fname

where Nunit is the Fortran unit to be used for file I/O and Fname is the name of the I/O file. Note that LPF, DCM, and BCF are all flow solvers and thus cannot be used simultaneously.

DCM is designed to work with a new Newton-Raphson solver NR1. The NR1 solver will be activated automatically. Other MODFLOW solvers (i.e., PCG2, GMG, DE4, SIP, etc) should not be included in the name file.

B.2 DCM Input Parameters

The structure of the DCM input file follows that of LPF. Because DCM only allows one diffuse layer and one conduit layer, vertical conductivity and vertical anisotropy parameters are not needed and are not recognized. In addition, LPF parameters related to drying and rewetting are not needed in DCM and should not be entered. DCM requires one additional global variable and two additional layer variables that are not required for LPF.

Many of the instructions that follow are copied from the LPF instruction. The DCM-specific changes and instructions are highlighted in blue. Note that DCM requires input for two layers. Layer 1 represents the conduit and Layer 2 the diffuse (matrix) system.

0. [#Text]
Item 0 is optional—"#" must be in Column 1. Item 0 can be repeated multiple times.
1. ILPFCB HDRY NPDCM
2. LAYTYP(NLAY)
3. LAYAVG(NLAY)
4. CHANI(NLAY)
5. FLOWLAW
6. [PARNAM PARTYP Parval NCLU]
7. [Layer Mltarr Zonarr IZ]
Each repetition of Item 7 is called a parameter cluster. Repeat Item 7 NCLU times.
Repeat Items 6-7 for each parameter to be defined (that is, NPDCM times).

A subset of the following two-dimensional variables is used to describe each layer. All the variables that apply to Layer 1 are read first, followed by Layer 2. If a variable is not required due to simulation options (for example, SS and SY for a completely steady-state simulation), then it must be omitted from the input file.

These variables are either read by the array-reading utility module, U2DREL, or they are defined through parameters. If a variable is defined through parameters, then the variable itself is not read; however, a single record containing a print code is read in place of the array control record. The print code determines the format for printing the values of the variable as defined by parameters. The print codes are the same as those used in an array control record. If any parameters of a given type are used, parameters must be used to define the corresponding variable for all layers in the model.

8. HK(NCOL,NROW)	If there are any HK parameters, read only a print code.
9. [HANI(NCOL,NROW)]	Include Item 9 only if CHANI is less than or equal to 0. If there are any HANI parameters, read only a print code.
10. [CRTG(NCOL,NROW)]	Include Item 10 only for Layer 1 when FLOWLAW is equal to 1. If there are no CRTG parameters, read only a print code.
11 [SS(NCOL,NROW)]	Include Item 11 only if at least one stress period is transient. If there are any SS parameters, read only a print code.
12. [SY(NCOL,NROW)]	Include Item 12 only if at least one stress period is transient and LAYTYP is not 0. If there are any SY parameters, read only a print code.
13. CDEX(NCOL,NROW)	Read Item 13 only for Layer 1. If there are any CDEX parameters, read only a print code.

ILPFCB – is a flag and a unit number.

If ILPFCB > 0, it is the unit number to which cell-by-cell flow terms will be written when “SAVE BUDGET” or a nonzero value for ICBCFL is specified in Output Control. The terms that are saved are storage, constant-head flow, and flow between adjacent cells.

If ILPFCB = 0, cell-by-cell flow terms will not be written.

If ILPFCB < 0, cell-by-cell flow for constant-head cells will be written in the listing file when “SAVE BUDGET” or a nonzero value for ICBCFL is specified in Output Control. Cell-by-cell flow to storage and between adjacent cells will not be written to any file.

HDRY – is not used in DCM, but should be present in the input.

NPDCM – is the number of parameters.

LAYTYP – indicates the layer type. Enter one value for each layer. Value 0 represents confined layer type, and nonzero value represents unconfined layer type.

LAYAVG – indicates the method for calculating intercell conductances. One value is needed for each layer.
0 – harmonic mean
1 – logarithmic mean
For a detailed description of the averaging methods, please refer to the User's Manual for MODFLOW2000. In DCM, these averaging methods apply only to the hydraulic conductivity. Upstream weighting of the saturated thickness is used in DCM to calculate the intercell conductances.

CHANI – contains a value for each layer that is a flag or the horizontal anisotropy. If CHANI is less than or equal to 0, then variable HANI defines horizontal anisotropy. If CHANI is greater than 0, then CHANI is the horizontal anisotropy for the entire layer and HANI is not read. If any HANI parameters are used, CHANI for all layers must be less than or equal to 0.

FLOWLAW – indicates the governing flow equation for conduits. Enter 0 for laminar flow (Darcy's equation) and 1 for turbulent flow (Darcy-Weisbach equation). The diffuse system is always modeled with Darcy's equation.

PARNAM – is the name of a parameter to be defined. This name can consist of 1 to 10 characters and is not case sensitive (i.e., any combination of the same characters with different case will be equivalent).

PARTYP – is the type of parameter to be defined. For the DCM Package, the allowed parameter types are

> HK – defines variable HK, horizontal hydraulic conductivity
> HANI – defines variable HANI, horizontal anisotropy
> SS – defines variable Ss, the specific storage
> SY – defines variable Sy, the specific yield
> CDEX – defines variable α, the linear exchange term between the conduit layer and the diffuse matrix layer. Enter for Layer 1.
> CRTG – defines the critical gradient for the onset of turbulent flow in the conduit. Enter for Layer 1 if the turbulent flow law is chosen.

PARVAL – is the parameter value.

NCLU – is the number of clusters required to define the parameter. Each repetition of Item 7 is a cluster (variables Layer, Mltarr, Zonarr, and IZ). There is usually only one cluster for each layer that is associated with a parameter.

LAYER – is the layer number to which a cluster definition applies.

MLTARR – is the name of the multiplier array to be used to define variable values that are associated with a parameter. The name “NONE” means that there is no multiplier array, and the variable values will be set equal to PARVAL.

ZONARR – is the name of the zone array to be used to define the cells that are associated with a parameter. The name “ALL” means that there is no zone array, and all cells in the specified layer are part of the parameter.

IZ – is up to 10 zone numbers (separated by spaces) that define the cells that are associated with a parameter. These values are not used if ZONARR is specified as “ALL.” Values can be positive or negative, but 0 is not allowed. The end of the line, a zero value, or a nonnumeric entry terminates the list of values.

HK– is the hydraulic conductivity along rows. HK is multiplied by horizontal anisotropy (see CHANI and HANI) to obtain hydraulic conductivity along columns.

HANI – is the ratio of hydraulic conductivity along columns to hydraulic conductivity along rows, where HK of Item 10 specifies the hydraulic conductivity along rows. Thus, the hydraulic conductivity along columns is the product of the values in HK and HANI. Read only if CHANI is not equal to 0.

CRTG – is the critical gradient for the onset of turbulence. Read only for Layer 1 and only if FLOWLAW > 1.

SS – is specific storage. Read only for a transient simulation (at least one transient stress period).

SY – is specific yield. Read only for a transient simulation (at least one transient stress period) and if the layer is convertible (LAYTYP is not 0).

CDEX – is the exchange term for flow between conduit and matrix system ($_0$). Enter for Layer 1 only.

B.3 Example Input File

The following shows an example of DCM input file,
DCM File,

```
#Example1 DCM package
50    -1E+30        3               Item 1:  ILPFCB HDRY NPLPF
 0 0                                Item 2:  LAYTYP
 0 0                                Item 3:  LAYAVG
 1 1                              Item 4:  CHANI
 0                                Item 5:  FLOWLAW
HK_0 HK   1  2                   Item 6:  PARNAM PARTYP PARVAL NCLU
 1 HK1 ZHK1 999                 Item 7:  LAYER MARRAY ZARRAY [zones]
 2 HK2 ZHK2 999
SS_0 SS   1  2                  Item 6:  PARNAM PARTYP PARVAL NCLU
 1 SS1 ZSS1 999                  Item 7:  LAYER MARRAY ZARRAY [zones]
 2 SS2 ZSS2 999
CDEX_0 CDEX   1  1         Item 6:  PARNAM PARTYP PARVAL NCLU
 1 CDEX1 ZCDEX1 999    tem 7:  LAYER MARRAY ZARRAY [zones]
       31        1(20G14.0)               -1  10: HK of layer 1
       31        1(20G14.0)               -1  11: HANI of layer 1
       31        1(20G14.0)               -1  12: Ss of layer 1
       31        1(20G14.0)               -1  13: CDEX of layer 1
       31        1(20G14.0)               -1  10: HK of layer 2
       31        1(20G14.0)               -1  11: HANI of layer 2
       31        1(20G14.0)               -1  12: Ss of layer 2
```

The values of parameters are defined in the associated multiplier file and zone file, respectively.

Multipler file,

```
#Example1 Multiplier file
 5
HK1
Constant           0.50    4: HK Multiplier array for layer 1
HK2
Constant           0.10    4: HK Multiplier array for layer 2
SS1
Constant         .0005     4: Ss Multiplier array for layer 1
SS2
Constant         .0001     4: Ss Multiplier array for layer 2
CDEX1
Constant           0.0001  4: CDEX Multiplier array for layer 1
```

Zone file,

```
#Example1 Zone file
 7
ZHK1
Constant           999    HK zone array for layer 1
ZHK2
Constant           999    HK zone array for layer 2
ZSS1
```

Constant 999 SS zone array for layer 1
ZSS2
Constant 999 SS zone array for layer 2
ZSY1
Constant 999 SY zone array for layer 1
ZSY2
Constant 999 SY zone array for layer 2
ZCDEX1
Constant 999 CDEX zone array for layer 1

B.4 NR1 Solver Input

The NR1 solver input is read from a file called nr1in.dat. The file must be named nr1in.dat. If the file is not present, default values will be used for all input parameters. The NR1 input is given below.

1. ITMXO HTOL
2. ATYPE LEVEL NVECTORS DETAIL
3. ITMAXI R2TOL RXTOL SXTOL

Definitions for the input parameters follow.

ITMAX0 – is the maximum number of outer iterations.

HTOL – is the head tolerance used to define convergence in the outer iterations.

ATYPE – is an integer-controlling selection of accelerator in a preconditioned conjugate gradient linear solver. Currently, the only allowed value is 4, which corresponds to the bi-conjugate gradient stabilized method. Alternative values may be available in future versions.

LEVEL – is the level of infill allowed in the incomplete lower-upper decomposition used for preconditioning. Recommended values are 1 or 0.

NVECTORS – is read but not currently used.

DETAIL – is an integer controlling output from the linear solver. Enter 0 for no output, 1 for summary output, and 2 for residual information at each inner iteration. Output is written to the file NR1OUT.DAT.

ITMAXI – is the maximum number of inner iterations.

R2TOL – is a convergence criterion based on the Euclidian norm of the residual.

RXTOL – is a convergence criterion based on the maximum residual.

SXTOL – is a convergence criterion based on the maximum scaled solution update.

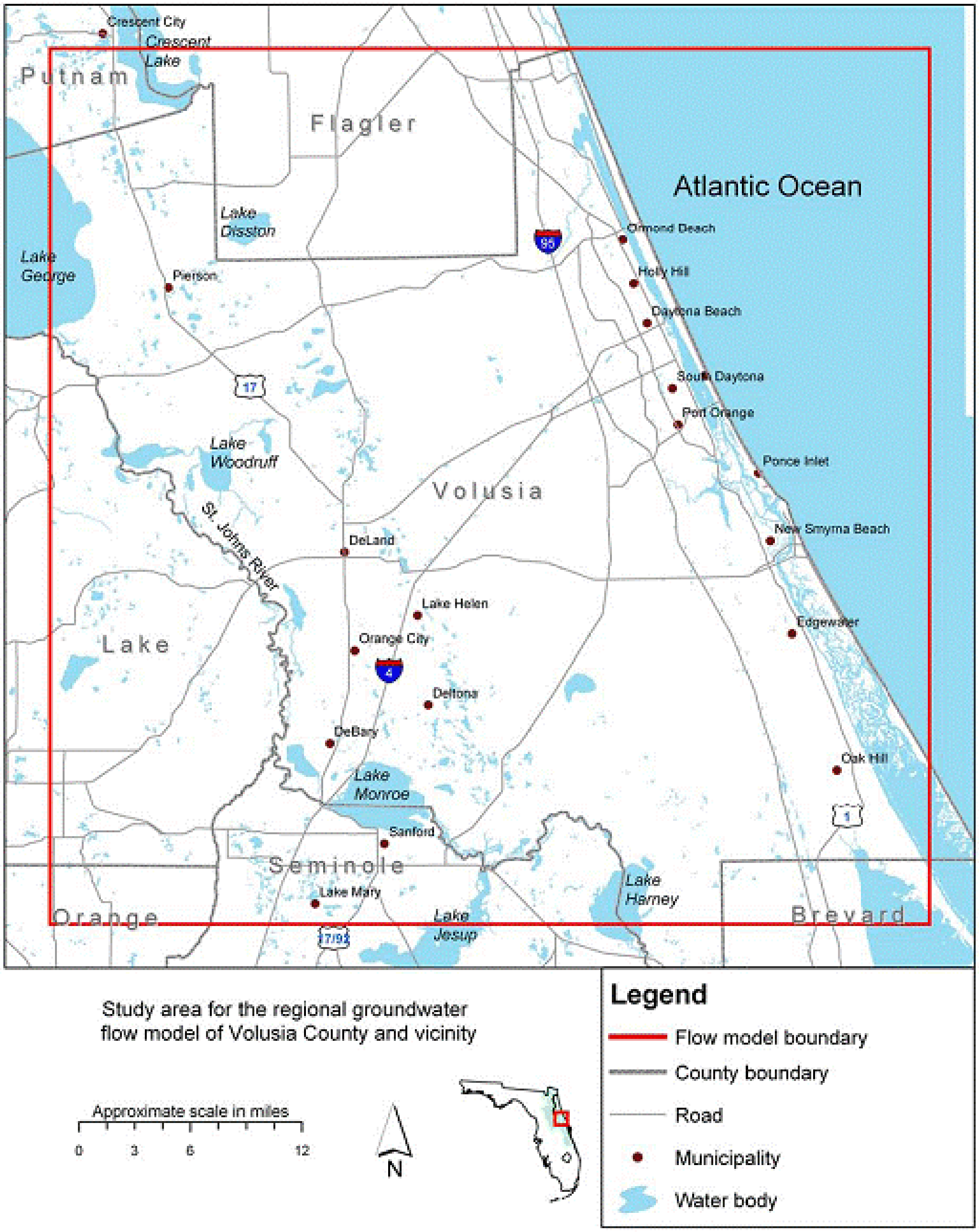

Figure 1. Study area of the dual continuum model of Volusia County and vicinity (Williams, 2006)

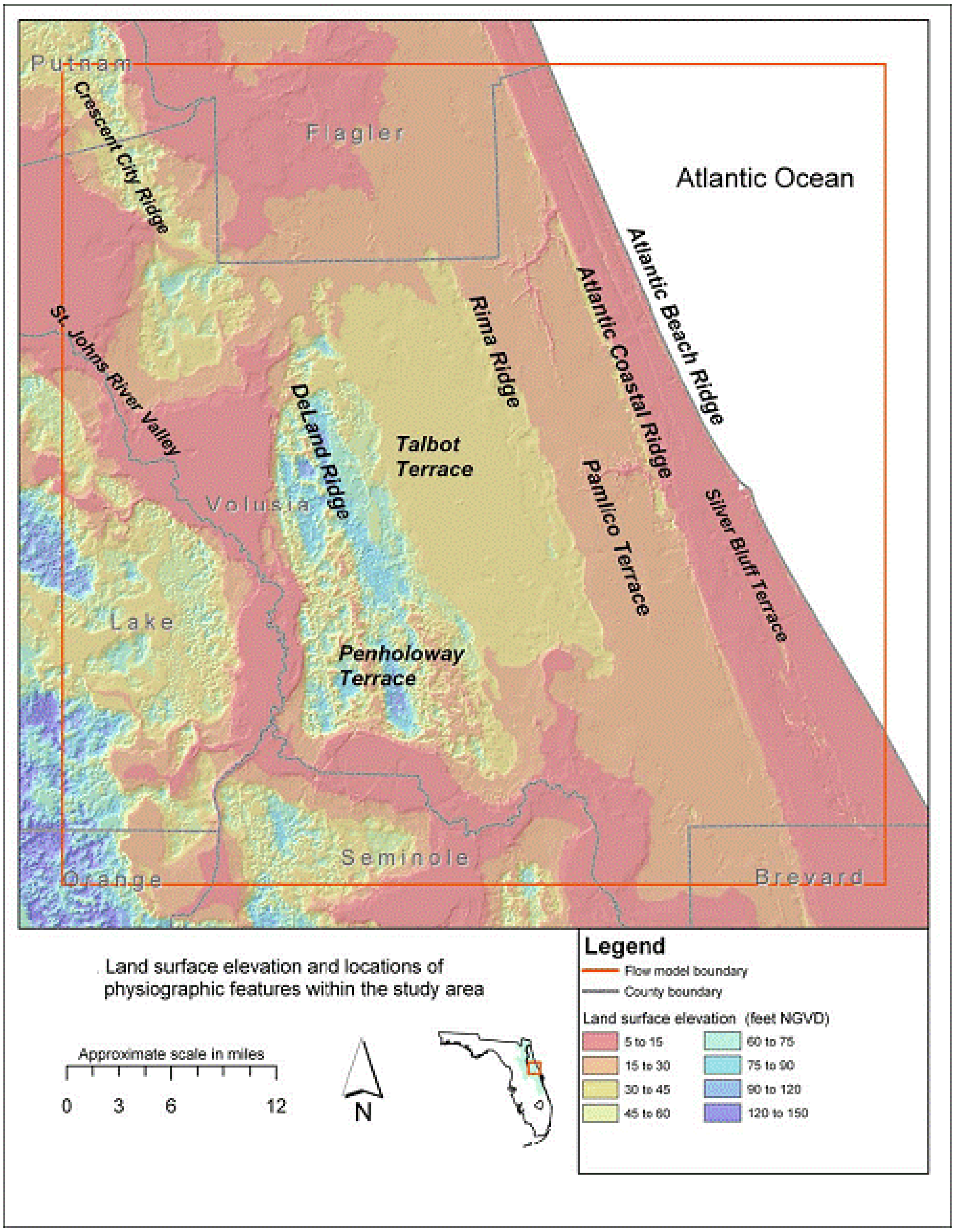

Figure 2. Land surface elevation and locations of physiographic features within the study area (Williams, 2006)

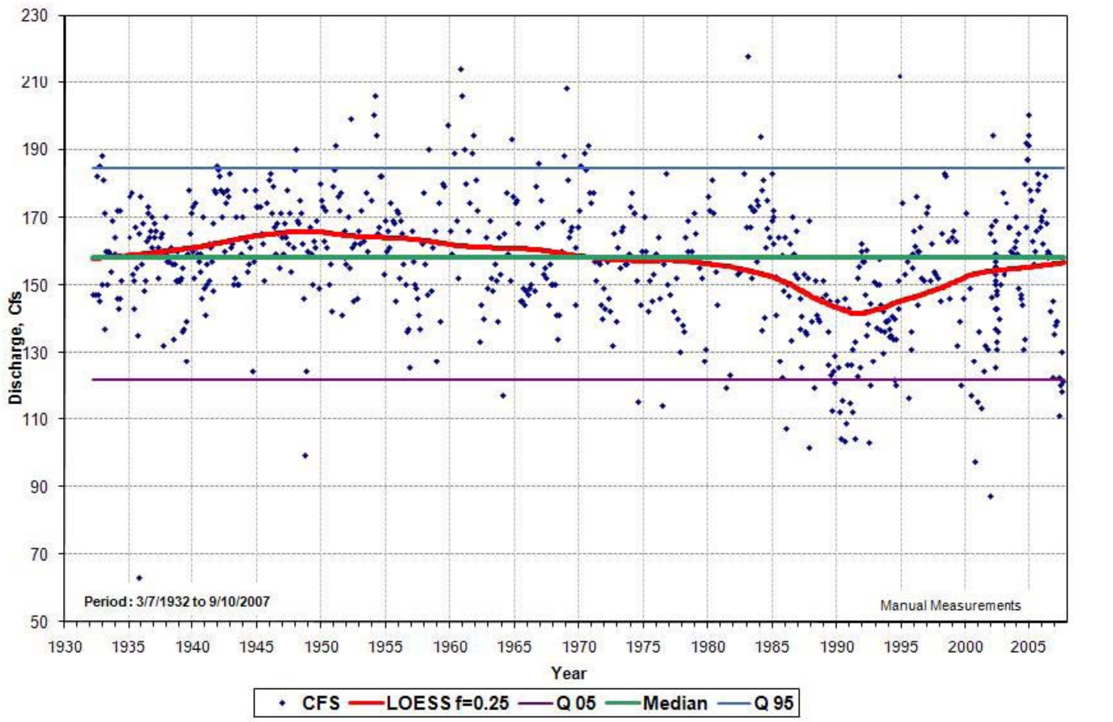

Figure 3. Manual discharge measurements for Blue Spring. Data are from the U.S. Geological Survey (Osburn, 2007).

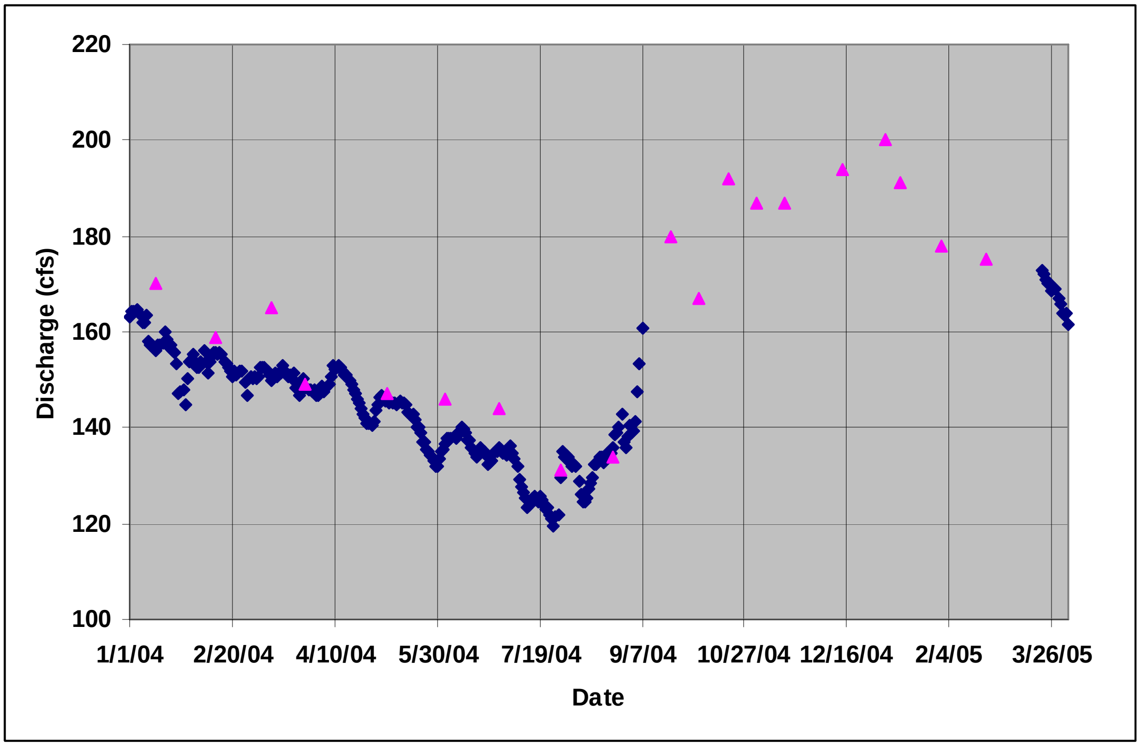

Figure 4. Blue Spring discharge based on current velocity measurements (blue squares) and manual measurements (pink triangles)

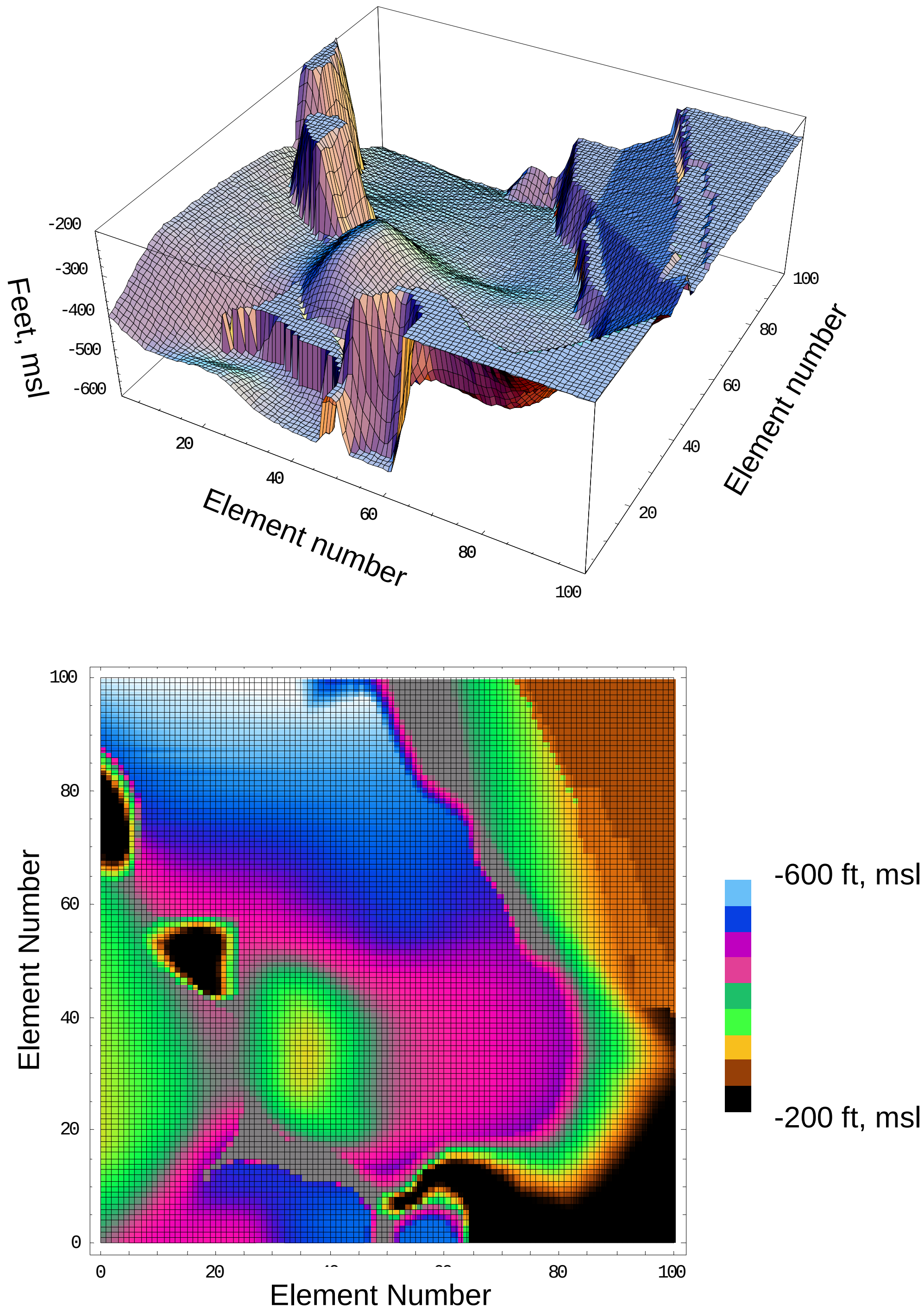

Figure 5. Elevation of the base of the Upper Floridan Aquifer (feet, msl) (Williams, 2006)

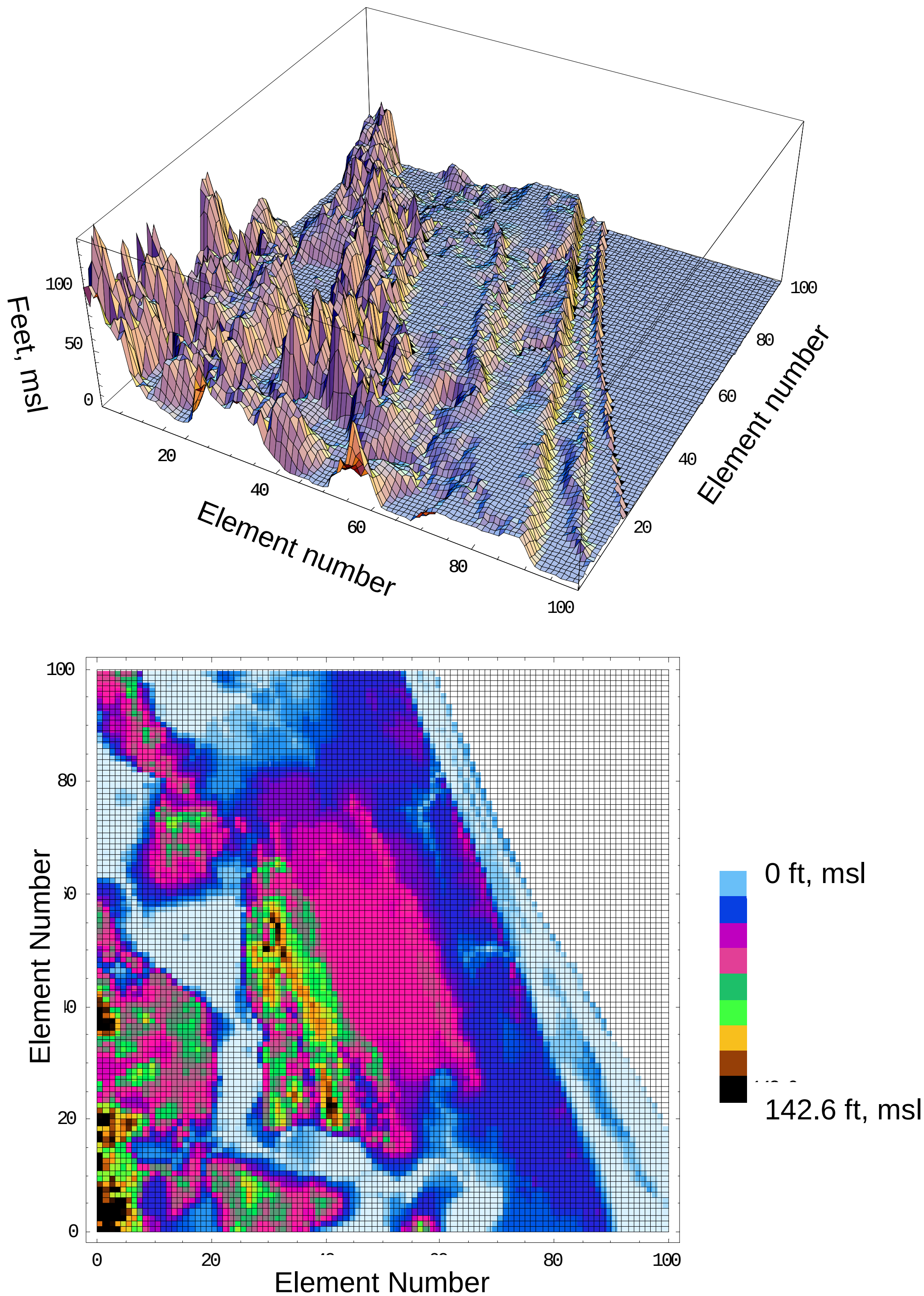

Figure 6. Topographic elevation of the study area (feet, msl) (Williams, 2006)

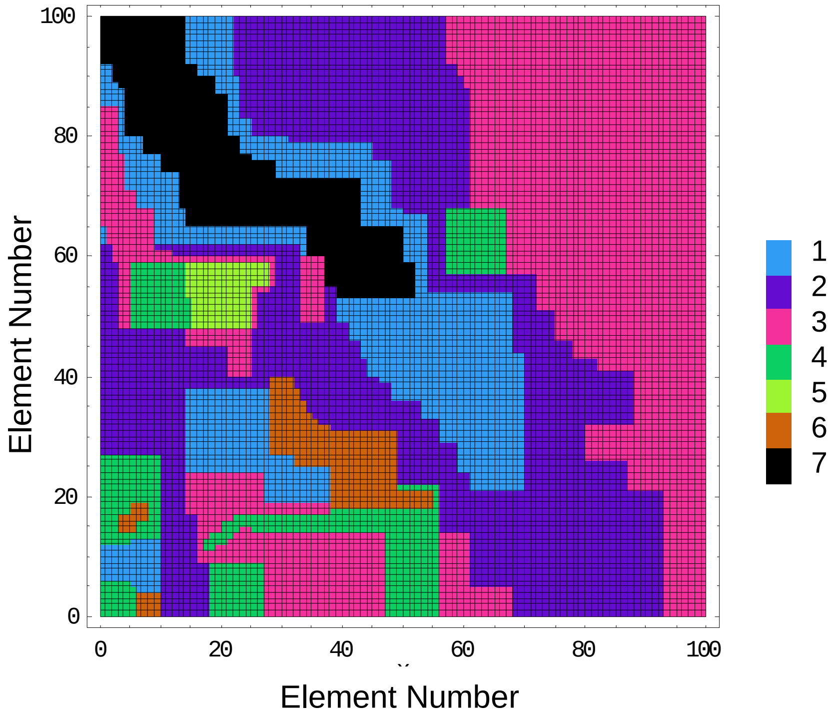

Figure 7. Distribution of diffuse layer hydraulic conductivity. Each color denotes one of the seven zones of hydraulic conductivity in the following order from lowest hydraulic conductivity to highest: black, blue, purple, pink, dark green, light green, gold.

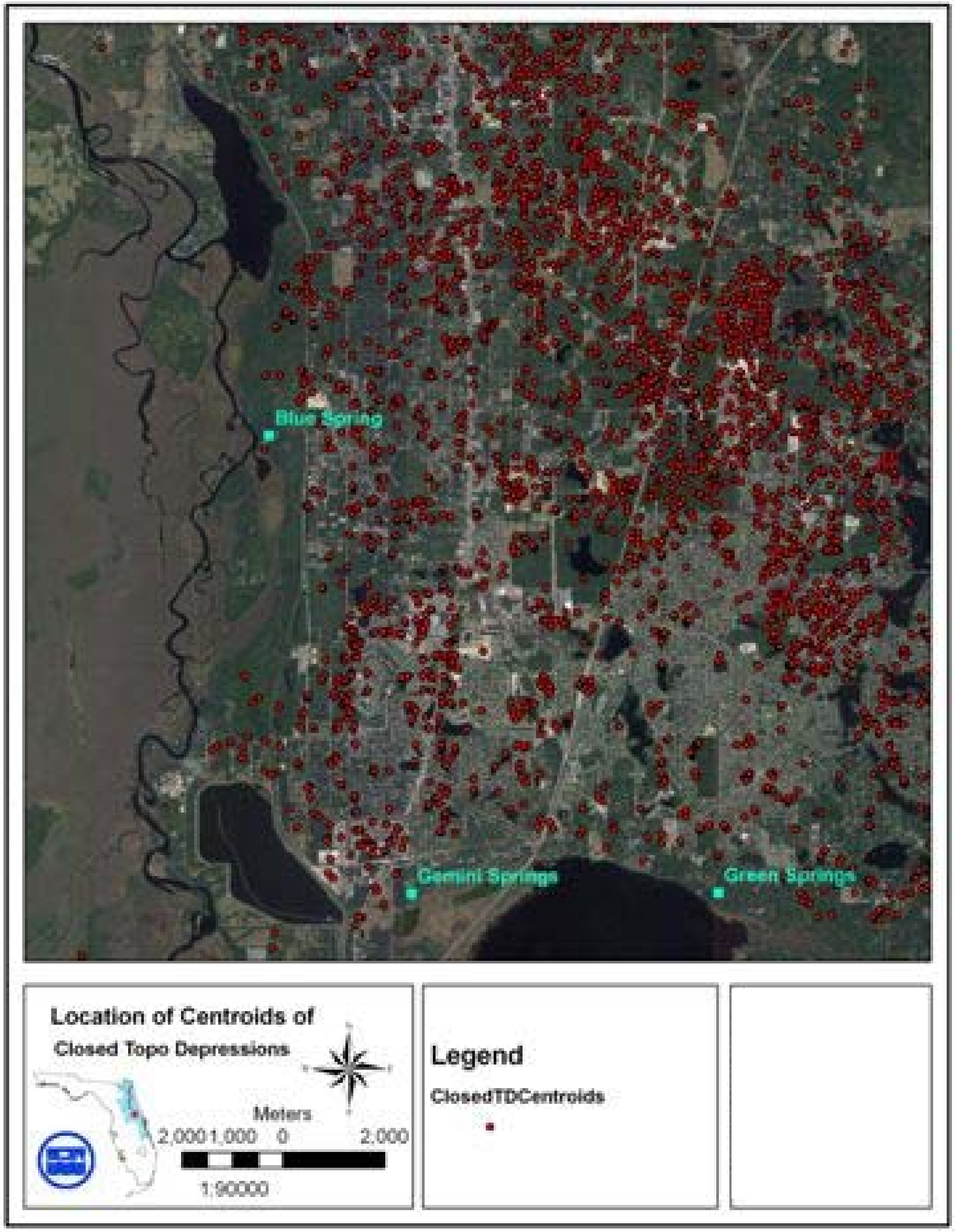

Figure 8. Locations of closed topographic depressions near Blue Spring (Williams, personal communication)

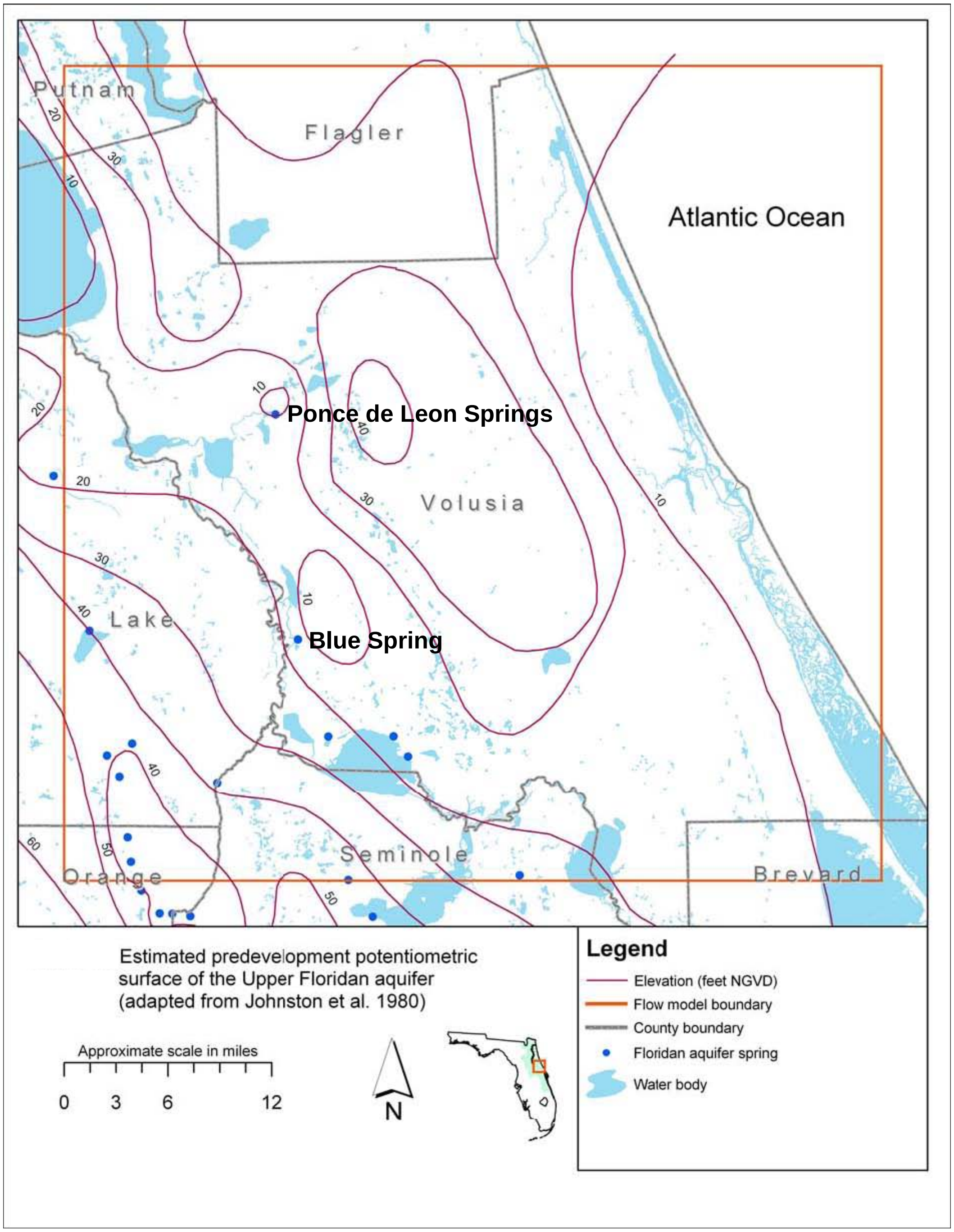

Figure 9. Estimated predevelopment potentiometric surface for the Upper Floridan Aquifer (feet, msl) (Williams, 2006)

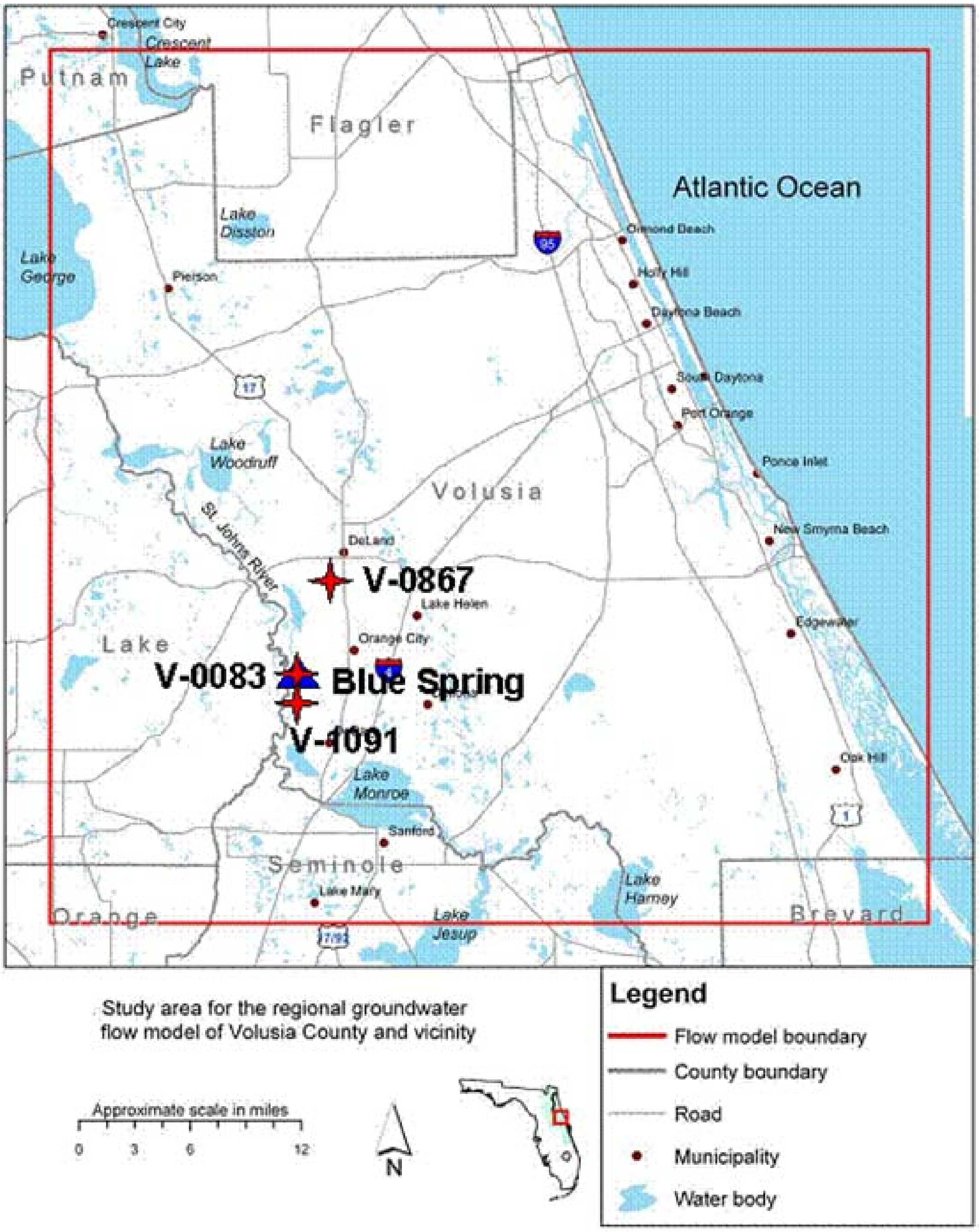

Figure 10. Locations of selected Upper Floridan Aquifer index wells in the Volusia County model domain. Index wells are denoted with red star and Blue Spring is denoted as a blue triangle (modified from Williams, 2006).

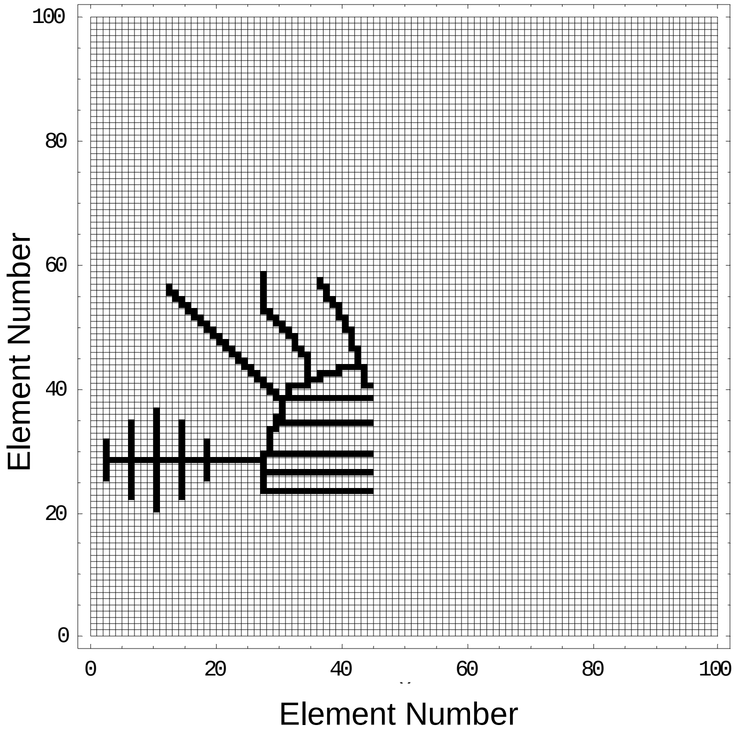

Figure 11. Conduit network assigned in MODFLOW-DCM basecase model. All segments were assigned uniform values.

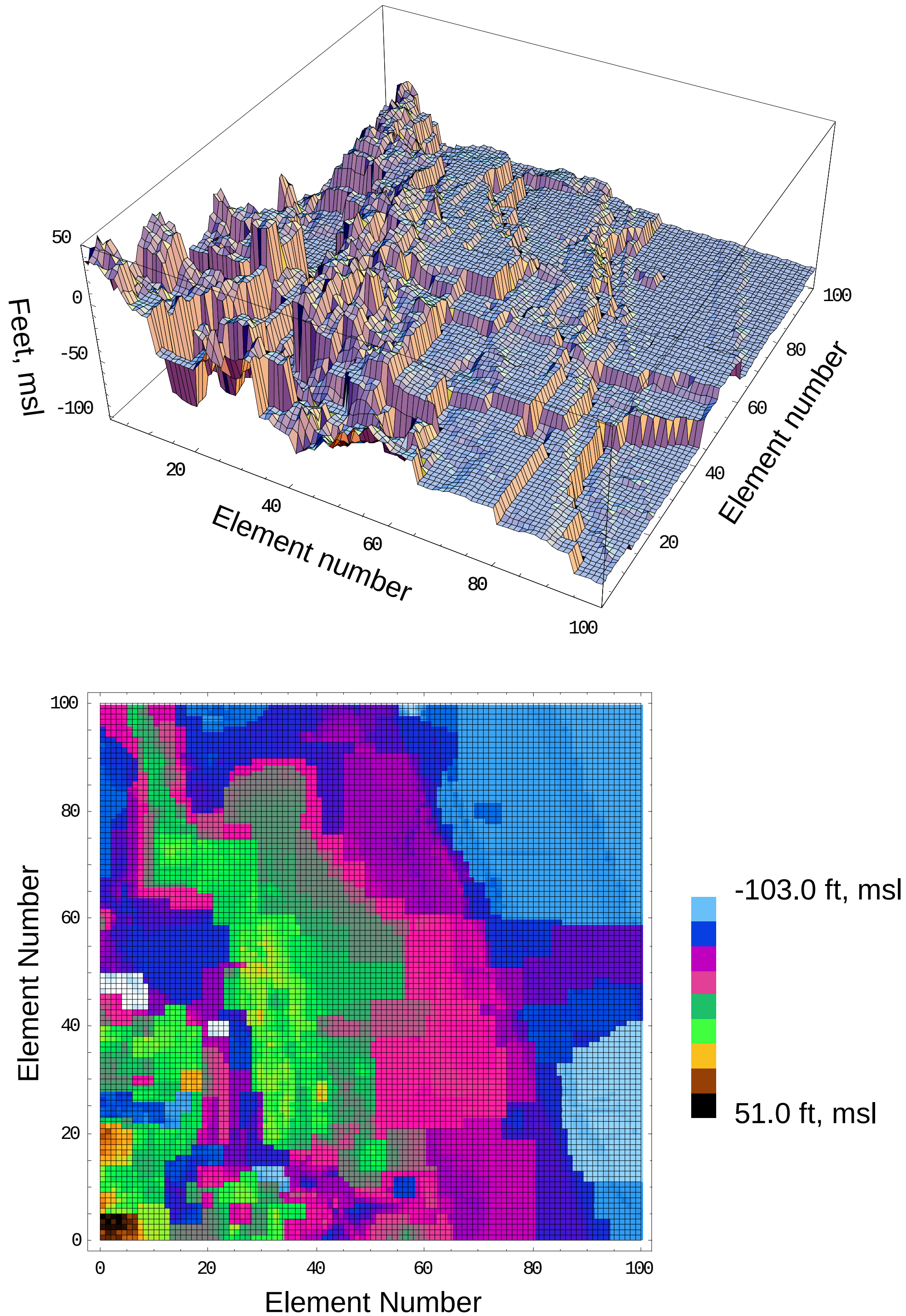

Figure 12. Basal elevation of the surficial aquifer (Williams, 2006). Also referred to as recharge distribution No. 1 (feet, msl). Note that recharge is interpreted to be a linear function of elevation.

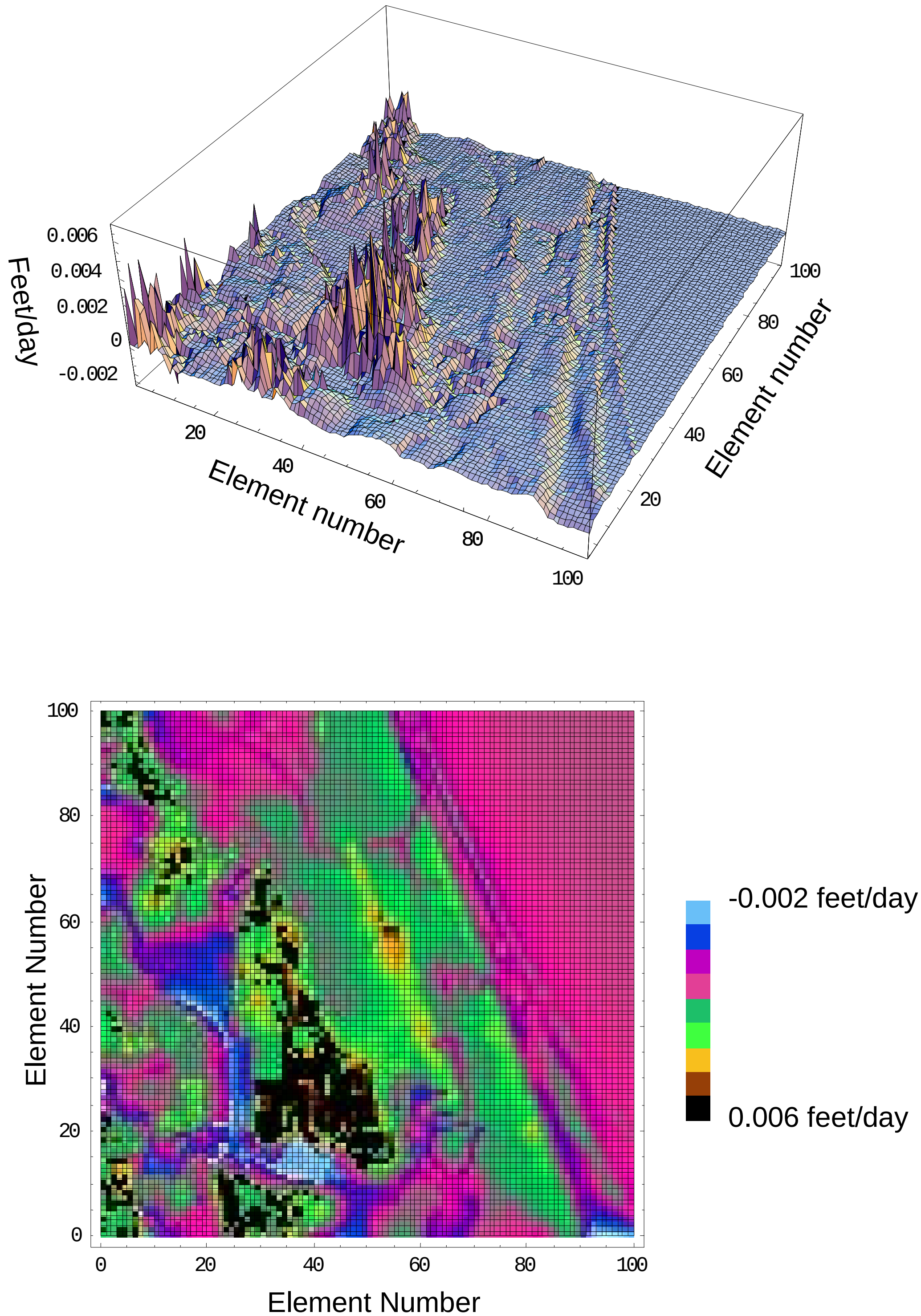

Figure13. Recharge distribution focused over the DeLand ridge. Also referred to as recharge distribution No. 2 (feet/day).

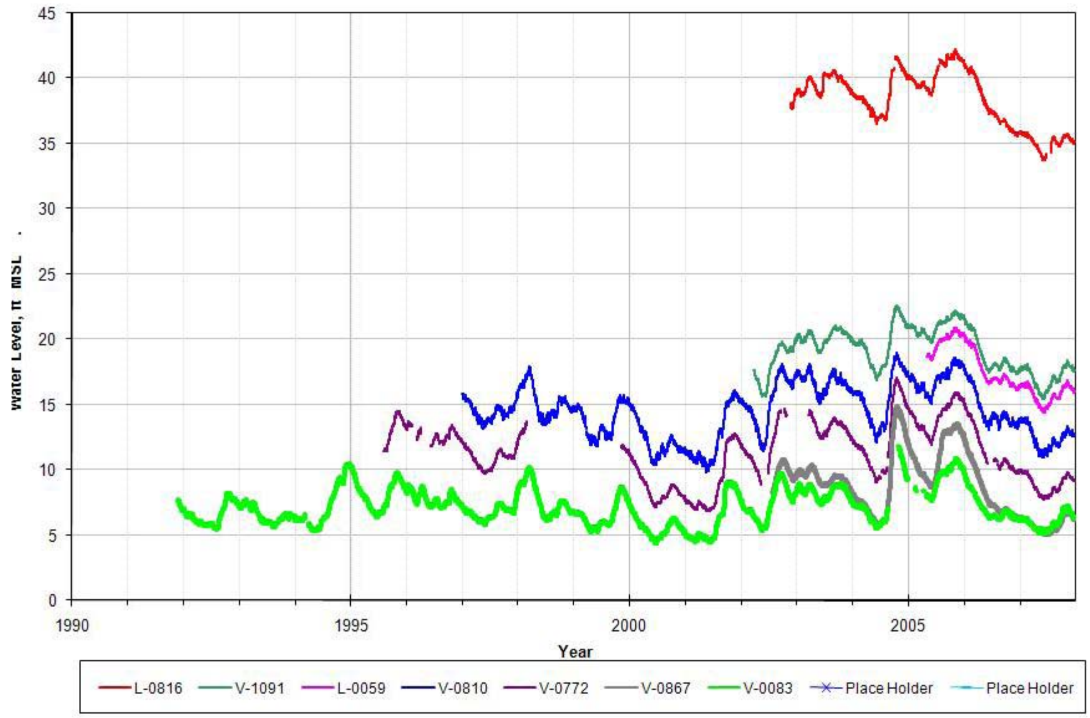

Figure 14. Comparison of groundwater elevations recorded at select wells near Blue Spring (Osburn, 2007)

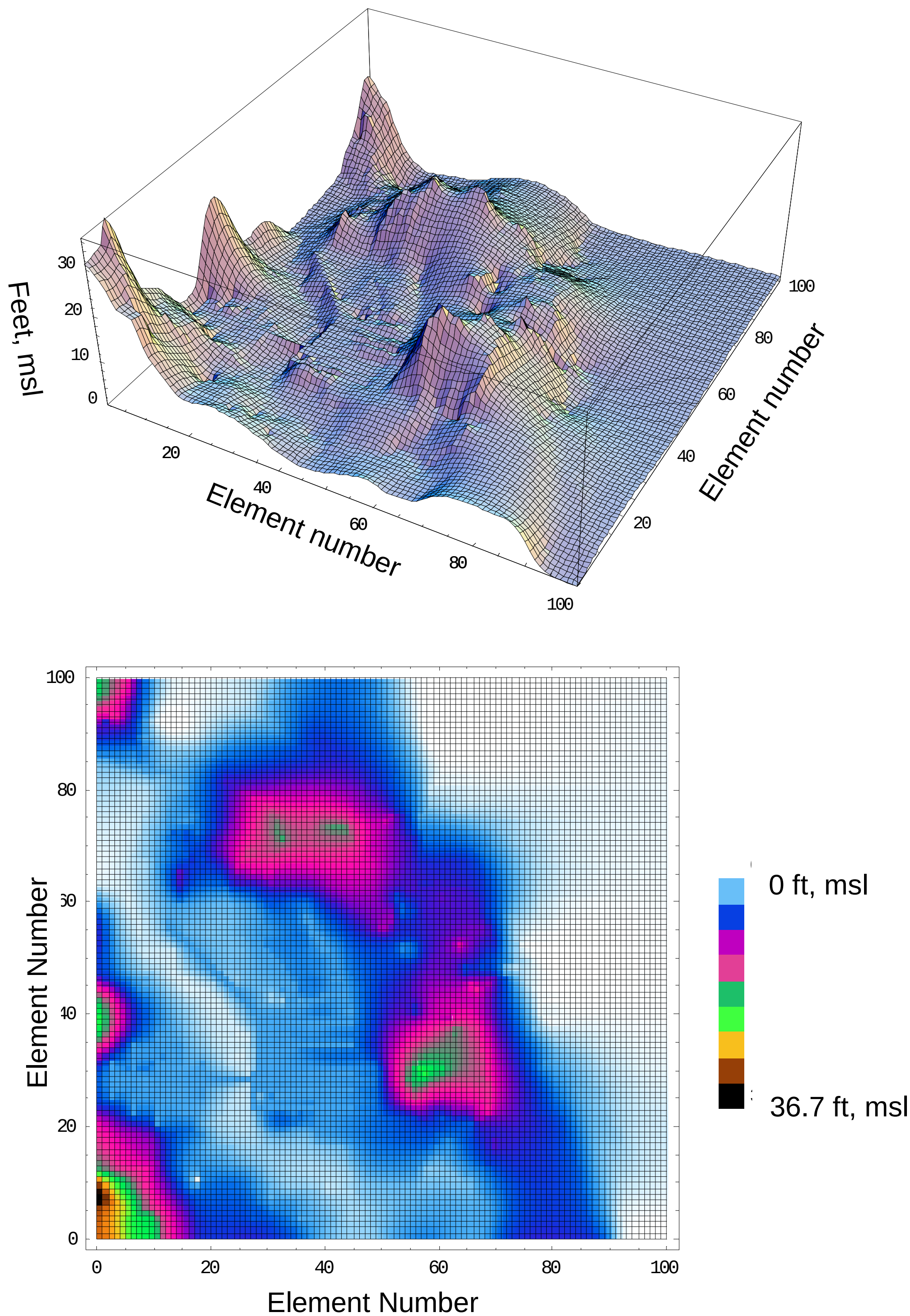

Figure 15. Basecase simulated potentiometric surface for the Upper Floridan Aquifer (feet, msl)

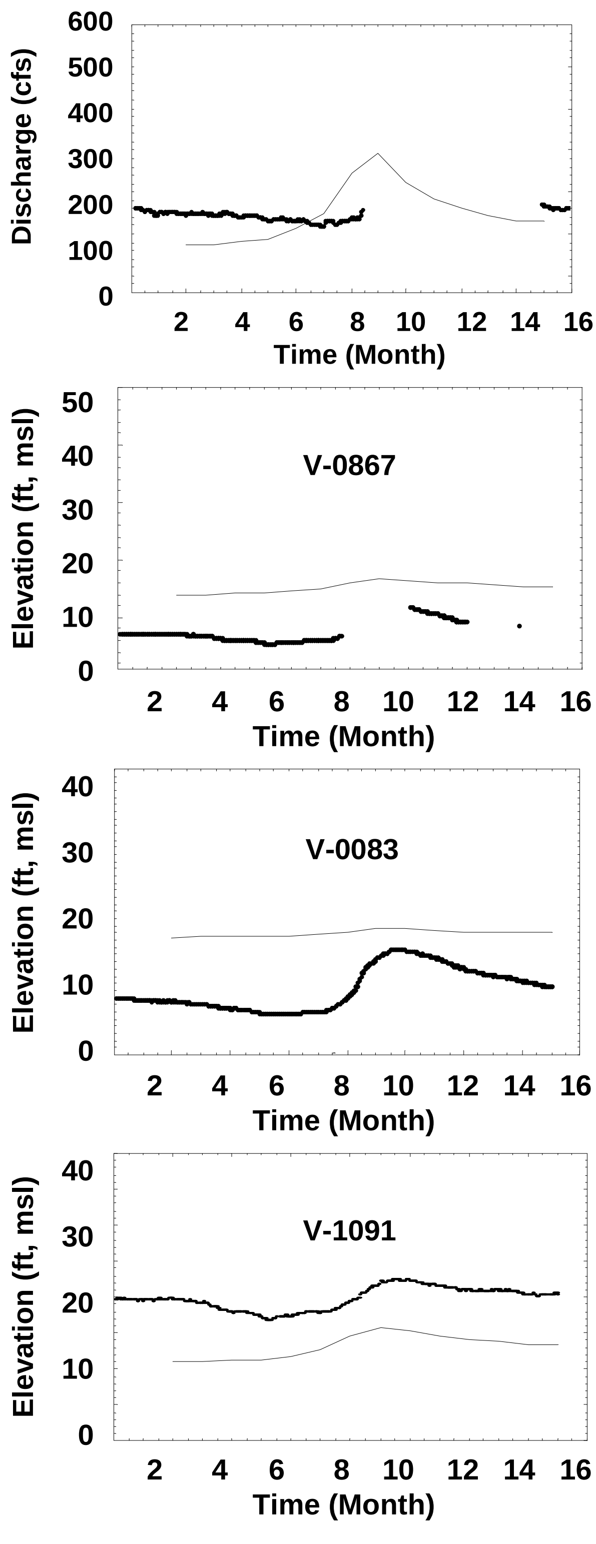

Figure 16. Target criteria and simulation results for the transient basecase model for the period January 1, 2004, through March 31, 2005. (a) Discharge at Blue Spring. (b) Groundwater elevation at V-0867. (c) Groundwater elevation at V-0083. (d) Groundwater elevation at V-1091. Light line is model simulation and dotted line is measured data.

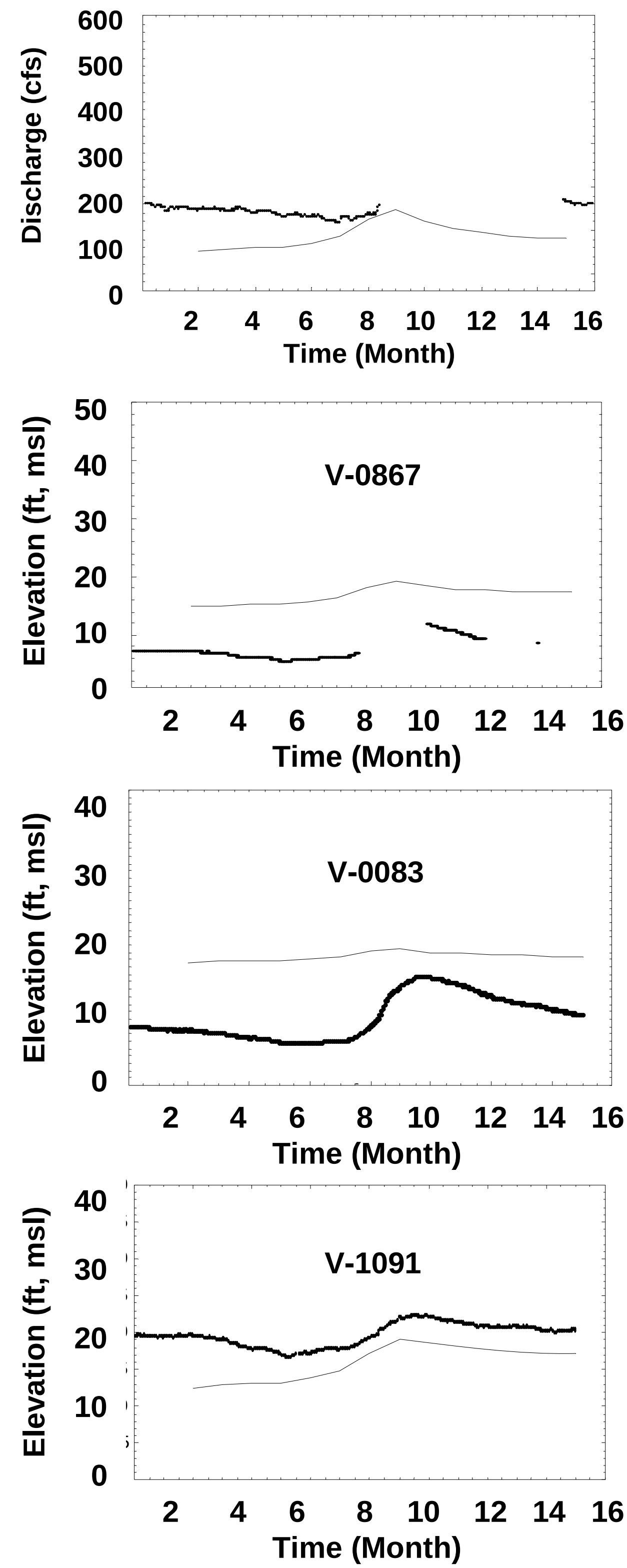

Figure 17. Target criteria and simulation results for the transient model with more uniform distribution of recharge for the period January 1, 2004, through March 31, 2005. (a) Discharge at Blue Spring. (b) Groundwater elevation at V-0867. (c) Groundwater elevation at V-0083. (d) Groundwater elevation at V-1091. Light line is model simulation and dotted line is measured data.

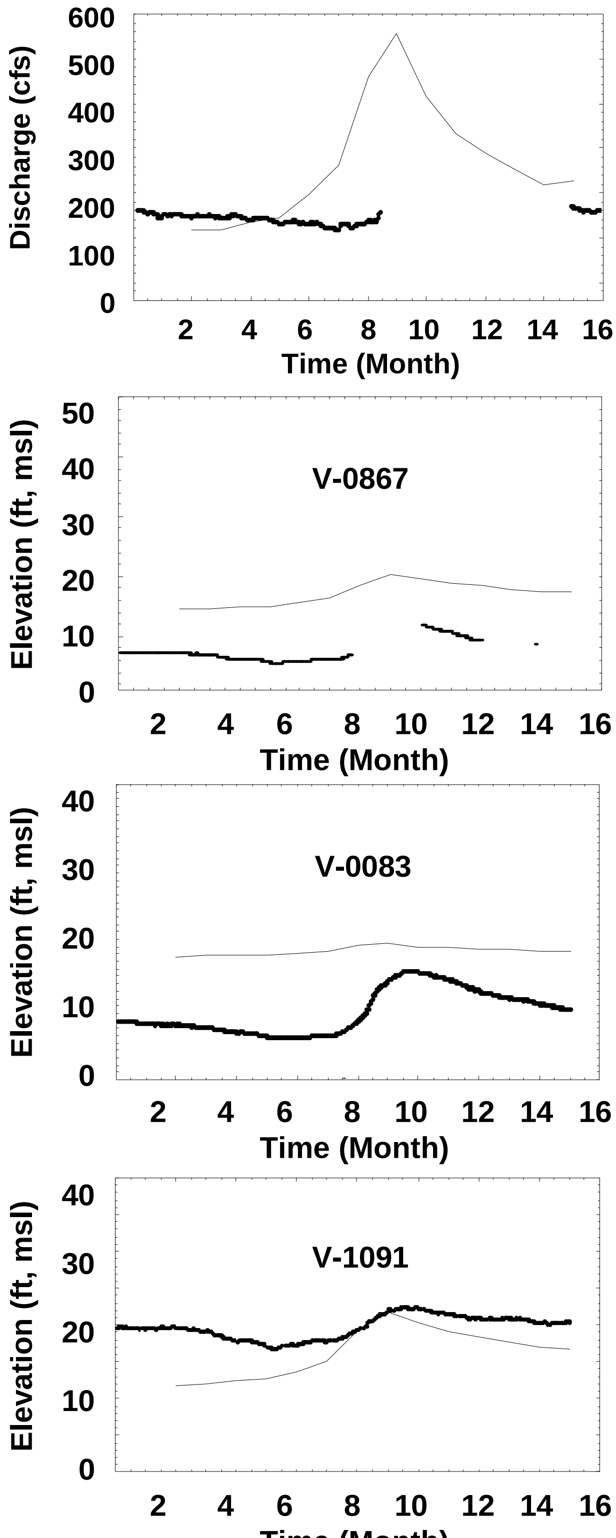

Figure 18. Target criteria and simulation results for the transient model with recharge doubled for the period January 1, 2004, through March 31, 2005. (a) Discharge at Blue Spring. (b) Groundwater elevation at V-0867. (c) Groundwater elevation at V-0083. (d) Groundwater elevation at V-1091. Light line is model simulation and dotted line is measured data

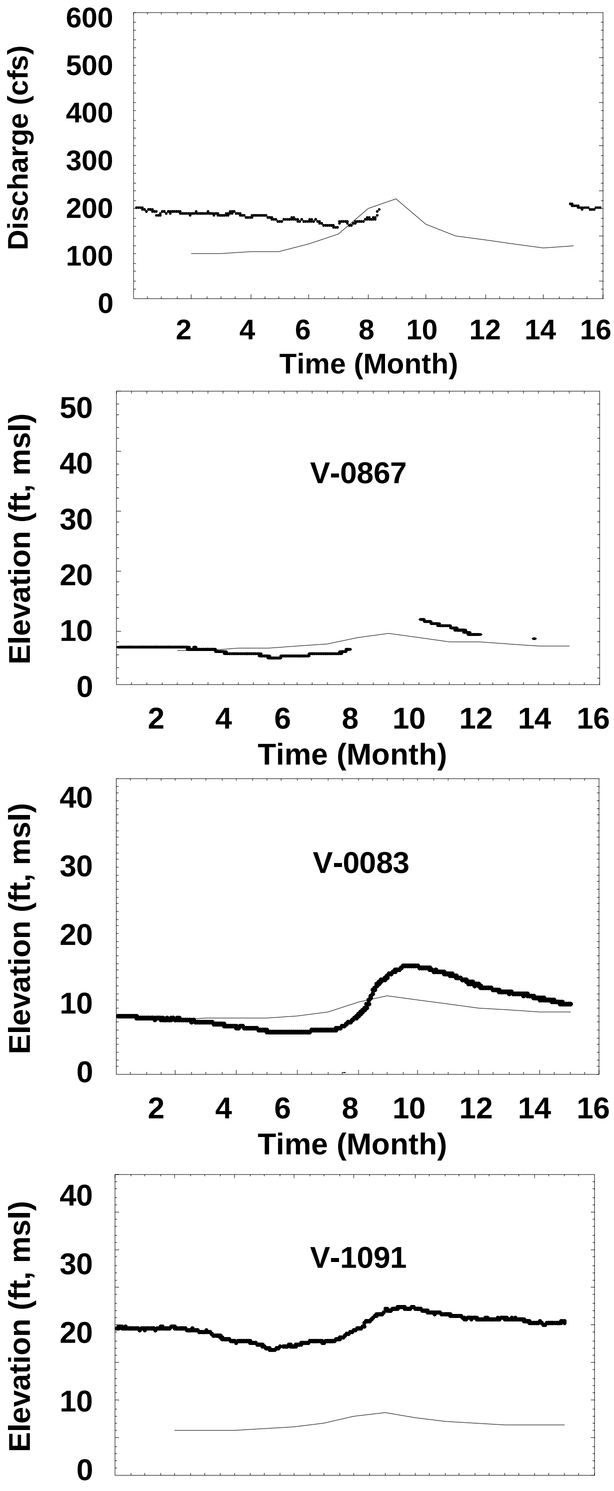

Figure 19. Target criteria and simulation results for the transient model with diffuse hydraulic conductivity increased by a factor of 10 for the period January 1, 2004, through March 31, 2005. (a) Discharge at Blue Spring. (b) Groundwater elevation at V-0867. (c) Groundwater elevation at V-0083. (d) Groundwater elevation at V-1091. Light line is model simulation and dotted line is measured data.

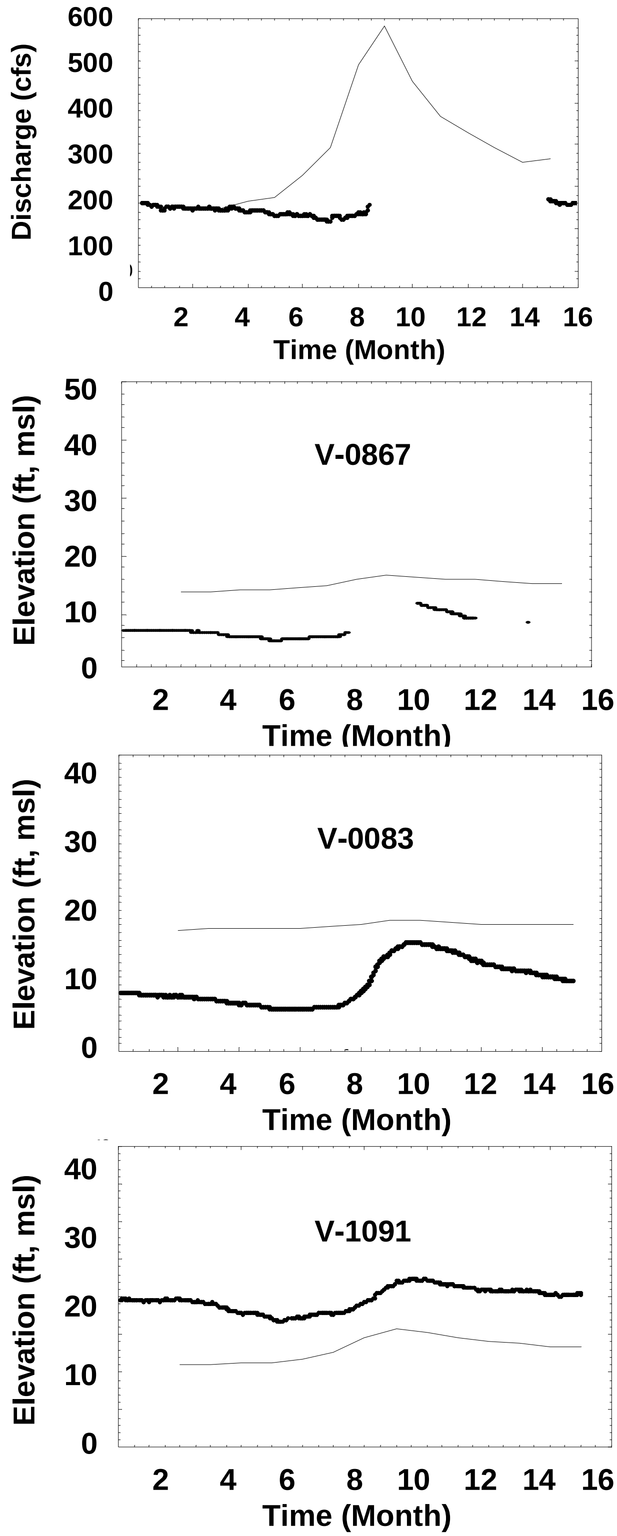

Figure 20. Target criteria and simulation results for the transient model with conduit conductivity doubled from 2.0×10^7 to 4.0×10^7 feet/day for the period January 1, 2004, through March 31, 2005. (a) Discharge at Blue Spring. (b) Groundwater elevation at V-0867. (c) Groundwater elevation at V-0083. (d) Groundwater elevation at V-1091. Light line is model simulation and dotted line is measured data.

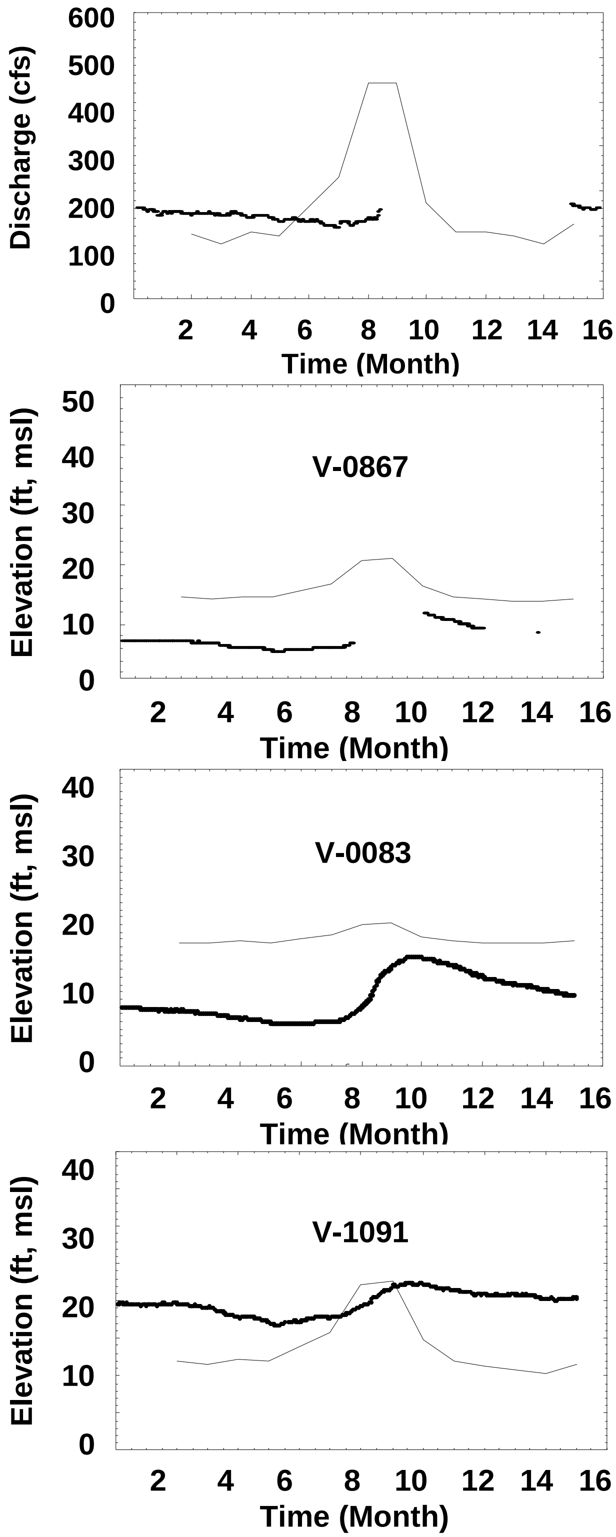

Figure 21. Target criteria and simulation results for the transient model with storage coefficients decreased from 0.05 and 0.01 in the basecase to 0.005 and 0.001, respectively for the period January 1, 2004, through March 31, 2005. (a) Discharge at Blue Spring. (b) Groundwater elevation at V-0867. (c) Groundwater elevation at V-0083. (d) Groundwater elevation at V-1091. Light line is model simulation and dotted line is measured data.

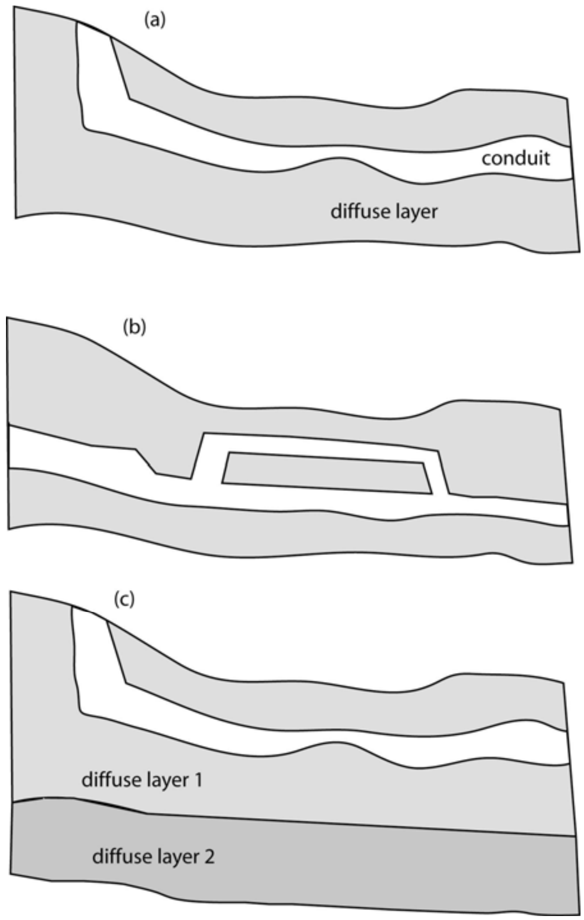

Figure A.1 Hypothetical cross sections illustrating the range of applicability of MODFLOW-DCM. MODFLOW-DCM will model a single-layer aquifer containing a single-level conduit system, as in (a). MODFLOW-DCM will not model a multilevel conduit system like that shown in (b) or a multiple-layer aquifer similar to the ones shown in (c) (Painter et al., 2007).