ground water

Evaluation of the MODFLOW-2005 Conduit Flow Process

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Abstract

The recent development of the Conduit Flow Process (CFP) by the U.S. Geological Survey (USGS) provides hydrogeologic modelers with a new tool that incorporates the non-Darcian, multiporosity components of flow characteristic of karst aquifers. CFP introduces new parameters extending beyond those of traditional Darcian groundwater flow codes. We characterize a karst aquifer to collect data useful for evaluating this new tool at a test site in west-central Florida, where the spatial distribution and cross-sectional area of the conduit network are available. Specifically, we characterize: (1) the potential for Darcian/non-Darcian flow using estimates of specific discharge vs. observed hydraulic gradients, and (2) the temporal variation for the direction and magnitude of fluid exchange between the matrix and conduit network during extreme hydrologic events. We evaluate the performance of CFP Mode 1 using a site-scale dual-porosity model and compare its performance with a comparable laminar equivalent continuum model (ECM) using MODFLOW-2005. Based on our preliminary analyses, hydraulic conductivity coupled with conduit wall conductance improved the match between observed and simulated discharges by 12% to 40% over turbulent flow alone (less than 1%).

Introduction

The karst research community has known that traditional numerical groundwater flow codes do not consider the non-Darcian, multiporosity components of flow in karst aquifers (Smith et al. 2005; Wilson 2002; Sasowsky 2000; Mohrlok et al. 1997; Mohrlok and Sauter 1997; Quinlan et al. 1995). The major limitations of these traditional codes are twofold: (1) Darcy's Law, used in traditional codes, does not account for turbulent flow that can occur in karst aquifers, and (2) the application of traditional laminar codes used with equivalent continuum models (ECM), which represent the bulk permeabilities for both the matrix and conduit network, can be an incorrect conceptualization for multiporosity karst aquifers depending on the scale and purpose of the groundwater flow model (White 1999). These limitations can result in noticeable discrepancies between observed and simulated aquifer heads in areas affected by the conduit network (Smith et al. 2005). For the Upper Floridan aquifer, the challenge is simulating discharge during periods of low recharge. Large hydraulic conductivity values are typically required to match simulated and observed discharges near large springs using laminar ECMs calibrated to average flow conditions. The inflated bulk hydraulic conductivity values used in laminar ECMs generally simulate a reduction of flow during periods of low recharge that is not corroborated by observed data (GeoTrans Inc. 1988a).

To address the limitations of laminar ECMs, the U.S. Geological Survey (USGS) recently developed the Conduit Flow Process (CFP) (Shoemaker et al. 2008), which

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when operated in Mode 1 couples a discrete conduit network to the matrix and uses the Darcy-Weisbach equation to simulate turbulent flow and the Hagen-Poiseuille equation for laminar flow in the conduit network. Fluid exchange between the matrix and the conduit network in CFP Mode 1 is considered with an iterative head-dependent flux between the conduit network and matrix (Shoemaker et al. 2008). The code introduces new parameters that require site characterization beyond that typically required for traditional laminar ECMs.

In this study, we characterize: (1) the potential for Darcian/non-Darcian flow using estimates of specific discharge compared with observed hydraulic gradients, and (2) the temporal variation for the direction and magnitude of fluid exchange between the matrix and conduit network before, during, and following convective and tropical storm activity using high-frequency (15 min) water level and temperature data measured from wells penetrating both the matrix and conduit network for a karst aquifer where the spatial distribution and physical properties of the conduit network are available. We evaluate CFP Mode 1 (Shoemaker et al. 2008) using a site-scale dual-porosity model (DPM) and compare the relative performance between CFP Mode 1 and a comparable laminar ECM using MODFLOW-2005 (Harbaugh 2005).

Test Site

The test site encompasses an internally drained, mantled karst terrain in the vicinity of Weeki Wachee, located near the Gulf of Mexico coastline of west-central Florida (Figure 1). The Upper Floridan aquifer underlies the site. Springs emanate from the aquifer and sinkholes, and under water caves occur within the Upper Floridan aquifer. Many of the springs are proposed to be former sinkholes (recharge points) that reversed into focused discharge points in response to sea level rise (Upchurch and Randazzo 1997). Multiple episodes of karstification during the Cenozoic Era occurred in response to sea level fluctuations (Florea et al. 2007). Former mixing zones, in addition to sea level fluctuations, may have produced the large, horizontal elliptically shaped conduits subparallel to depositional layers, circular chambers, and vertical elliptically shaped conduits normal to depositional layers (Reeder and Brinkmann 1998). Passage widths can exceed 15 m at SP-1 and at the outermost mapped portions of SP-2 (Karst Underwater Research, Inc. 2008a; Champion and Starks 2001). The conduit network at the site is perennially water filled, even when cessation of discharge occurs at SP-2 during drought conditions.

Average matrix hydraulic conductivities (10^{-6} m/s) measured from core samples of limestone in the Upper Floridan aquifer (Florea 2006; Florea and Vacher 2007) are high relative to mean matrix values for comparable volumes measured for other karst aquifers (i.e., 10^{-8} m/s for the San Antonio segment of the Edwards aquifer in south-central Texas, Mace and Hovorka 2000; Halihan et al. 2000, and 10^{-11} m/s in the Ste. Genevieve Formation in central Kentucky; Worthington et al. 2000).

The site has wet and dry seasons. The wet season, which extends from June through September, commonly produces locally intense rainfall events associated with convective activity and occasional regional-scale events associated with tropical storm activity (Jordan 1984). During the course of this study, Tropical Storms Frances and Jeanne made landfall as hurricanes on the southeastern peninsula of Florida but were downgraded to tropical storms before passing over the study area.

The focus of this study was placed in the vicinity of SP-1, a first magnitude ($\geq$3 m^3/s) spring (Scott et al. 2004; Meinzer 1927), and SP-2, locally referred to as Little Spring, or Twin Dees, (Scott et al. 2004), sometimes spelled Twin D's (Hill 2008). Twin D's under average flow conditions and during the monitoring program is a third magnitude ($\leq$0.3 m^3/s) spring (Hill 2008; Meinzer 1927). However, during the course of the study, flow occasionally exceeded 0.3 m^3/s at SP-2 (second magnitude) (Hill 2008; Meinzer 1927). Both springs

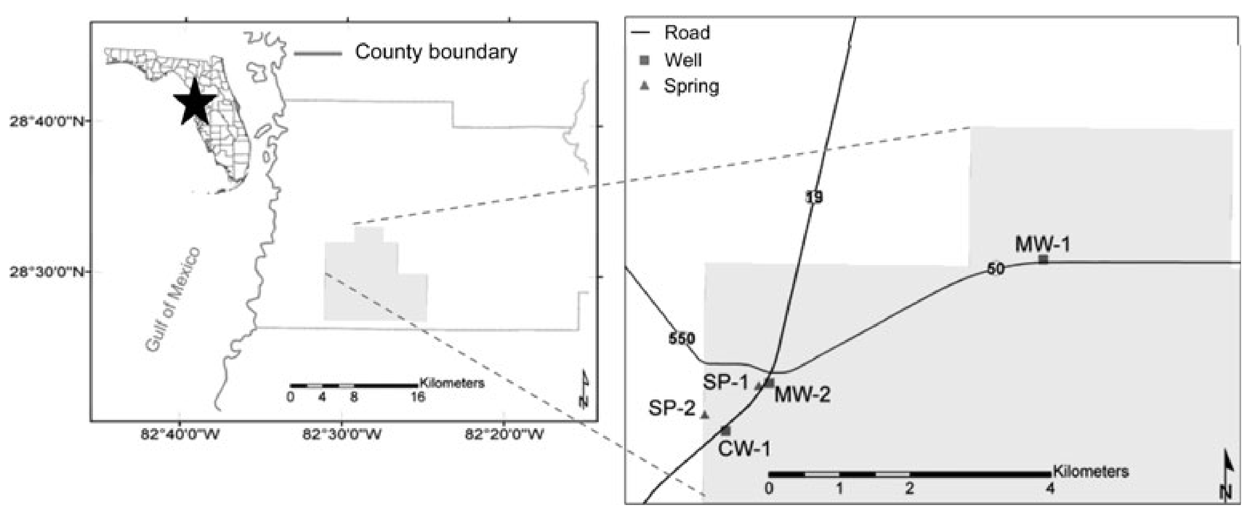

Figure 1. Location and site maps.

discharge fresh water (Champion and Starks 2001). The spring basins for SP-1 and SP-2 have not been rigorously delineated with dye-trace testing.

Approach

The first task involved determining whether a numerical code that simulates both laminar and turbulent flows was appropriate for the site. Estimates of Reynolds numbers and groundwater velocities through quantitative dye-trace testing were not available as they have been in previous studies at other locations (Hazlett et al. 2004; Kincaid et al. 2004). However, information pertaining to conduit dimensions for both SP-1 and SP-2 are available as the under water caves have been partially surveyed by cave divers (Karst Underwater Research, Inc. 2008a; Champion and Starks 2001). In addition, discharges from SP-1 and SP-2 are available. Therefore, estimates of specific discharge in the conduit network underlying SP-1 and SP-2 were calculated for two cave diameters. Diameters of 0.9 and 5 m were selected based on passage widths described by cave divers (Karst Underwater Research, Inc. 2008a; Champion and Starks 2001). Discharges for SP-1 and SP-2, Q, were divided by the cross-sectional area, A, to estimate specific discharges, v, where $v = Q/A$. The hydraulic gradients between a conduit well (CW-1) located 795 m from SP-1 and 386 m from SP-2 (Figure 1) were then plotted with specific discharge estimates with the purpose of identifying deviations from nonlinearity, which would indicate non-Darcian or turbulent flow.

The second task focused on evaluating the temporal variation for the direction and magnitude of fluid exchange between the matrix and conduit network. The direction and magnitude of fluid exchange between the matrix and conduit network were evaluated by collecting high-frequency (15 min) water level and temperature data from monitoring wells penetrating the matrix and conduit network.

The third task involved developing a site-scale DPM using CFP Mode 1 (Shoemaker et al. 2008) version 1.2.01 compiled on February 12, 2008. The performance of CFP Mode 1 relative to a comparable laminar ECM using MODFLOW-2005 (Harbaugh 2005) was evaluated in terms of simulated discharges.

Data Collection

The high-frequency (15 min) monitoring program extended from June through November of 2004 with less frequent monitoring (primarily daily water level measurements and monthly discharge measurements) continued through May 2006. Less frequent monitoring occurred at MW-2 during the low-frequency monitoring period due to problems with the equipment. The high-frequency monitoring period included two local-scale intense storm events (hours) associated with convective storms and two regional-scale, relatively longer duration (days) events associated with tropical storms. The less frequent monitoring period included observing a cessation of flow at SP-2 in May 2006 during drought conditions.

Two wells intercepting the matrix network (MW-1 and MW-2), one well intercepting the conduit network (CW-1), and two springs (SP-1 and SP-2) were instrumented with data loggers (Figure 1). The monitoring wells are within 6 km of the springs. Water levels were recorded at 15-min intervals in MW-1, MW-2, and CW-1. Temperature was recorded at 15-min intervals in MW-2, CW-1, SP-1, and SP-2. Verification checks on instrument water level measurements using a hand tape at MW-2 and CW-1 indicate that recorded levels are, on average, accurate to within ± 0.03 m. Temperature data are accurate to $\pm 0.15^{\circ}$C. Water levels at MW-1 (site id 283201082315601) and pool stage data at SP-1 (site id 02310500) are maintained by the USGS. Pool stage data for SP-2 are maintained by the Southwest Florida Water Management District (SWFWMD).

Caliper logs were collected to verify that CW-1 intercepts the conduit network and MW-1 and MW-2 intercept the rock matrix. Caliper and video logs confirm that CW-1 intercepts a horizontal conduit with a height of 8 m (Hill 2008).

Discharge measurements at SP-2 were initially performed on a weekly basis but were gradually decreased to a monthly basis as measured discharge rates did not vary appreciably between weekly measurements. In an effort to capture the storm response of SP-2, discharge measurements were performed 3 to 5 d before and following the passage of both tropical storms. Discharge measurements were not performed for SP-1 as a rating curve is currently used to estimate discharge (Knochenmus and Yobbi 2001).

Fifteen minute rainfall was compiled by OneRain Inc. for the SWFWMD. The rainfall data combine Doppler radar estimates of rainfall distribution with rainfall quantities recorded at local rain gauges (Hoblit and Curtis 2005).

Model Design and Calibration

The ECM and CFP Mode 1 models consisted of 25 monthly stress periods. The first stress period was set to steady-state conditions with the remaining 24 stress periods set to transient conditions spanning from June 2004 through May 2006. The time frame selected for the transient stress periods capture conditions before, during, and after the passage of two tropical storms (Frances and Jeanne) in 2004 and a cessation of flow for SP-2 in May 2006 during drought conditions. Collecting data and simulating flow under these extreme hydrologic conditions, ranging from high recharge events to a drought in 2006, provide a fairly rigorous evaluation for the performance of CFP Mode 1, as well as a unique opportunity to understand aquifer response.

The model boundaries were set to no-flow where hydraulic boundaries occur and as general-head boundaries where lateral flows occur across boundaries on portions of the northern, southern, and eastern model boundaries. Specified-head boundaries were set along the coast on most of the western boundary of the model, whereas general-head boundaries were used along the portions of the western boundary closest to land. Drains (both springs and diffuse swamp discharge) were simulated using the drain package. Quantities for swamp discharge are not well known for the site. Recharge distribution and quantities were determined using 15-min OneRain data. Net recharge (evapotranspiration subtracted from rainfall) was applied to the uppermost model layer. Table 1 shows the hydrogeologic framework for the site with the corresponding model layer.

The model was calibrated to monthly discharges at SP-1 and SP-2 and to monthly aquifer water levels using 32 observation wells within the Upper Floridan aquifer. Parameters were kept constant between the CFP Mode 1 and ECM with the exception of hydraulic conductivity, conduit wall conductance, which permits fluid exchange between the matrix and conduit network, and the critical Reynolds numbers. The range of hydraulic conductivity values (from 4 to 3810 m/d) simulated in the groundwater flow models are from 2 to 5 orders of magnitude higher relative to measurements for core-size matrix samples from the Ocala limestone (Florea 2006; Florea and Vacher 2007). In this study, low weight was applied to estimates based on aquifer performance tests, as these data were fairly limited and assumptions, as well as poor conditions, may have affected some of the results (Hill 2008). Our assumption of applying higher hydraulic conductivity values relative to values obtained from core samples is supported by Kiraly (1975) who reports that permeabilities increase with scale in multiporosity karst aquifers. The range for hydraulic conductivity values are the same for both models, but vary in the vicinity of SP-1 and SP-2 due to the inclusion of the conduit network in CFP Mode 1. Quantitative dye-trace tests performed in the vicinity of Sulfur Springs in west-central Florida and the Woodville Karst Plain in northwest Florida vary from 2200 to 6000 m/d (Wallace 1993; Kincaid et al. 2004) and are comparable with hydraulic conductivities in the groundwater flow models developed for this study.

Many types of data were used to define hydraulic conductivity zones. These data include: a physical inventory of surface karst features (springs, water-filled cave entrances, and sinkholes), fracture traces inferred from the alignment of closed topographic depressions, elevations of conduits interpreted from caliper logs and under water cave-survey data, ratios of conduit heights interpreted from the borehole porosity descriptions, troughs in aquifer water levels within the Upper Floridan aquifer, and hydrogeologic data consisting of stratigraphic changes and discharge/well hydrographs (Hill and Martin 2008).

The conduit network was explicitly incorporated into CFP Mode 1 using cave-survey data provided by Karst Underwater Research, Inc. (2008b) and were extrapolated 2 km beyond the terminus of the survey data (Figure 2) as the cave passages are know to extend further (Karst Underwater Research, Inc. 2008a). Conduits located further than 2 km from the terminus of the survey data were not explicitly incorporated into CFP Mode 1, but rather represented as the bulk hydraulic conductivities for the matrix and conduits similar to that typically used in ECMs. Conduit diameters in the CFP Mode 1 model ranged from 15 to 61 m. A more detailed discussion of model design and calibration as well as sensitivity analyses performed on model parameters is provided in Hill (2008). Both the ECM and CFP Mode 1 data sets are available as supporting information.

Results

Darcian-Non-Darcian Flow

Plots of specific discharge using conduit diameters of 0.9 and 5 m vs. hydraulic gradient indicates that turbulent flow likely occurs in the narrower cave passages underlying SP-2 (Figure 3) as a departure from linearity occurs for conduit diameters of 0.9 m. The narrower cave passages underlying SP-1 show linearity, indicating laminar flow. Estimates based on the larger diameter cave passages (5 m) suggest laminar flow

Table 1
Hydrogeologic Framework for the Site with the Corresponding Model Layer (Modified from Miller 1986)

Epoch	Stratigraphic Unit	Description	Aquifer/Confining Unit	Model Layer	
Pliocene-recent	Undifferentiated sands	Quartz sand and residual clays	Surficial aquifer	Mantle	1
Miocene	Hawthorn group	Clays, silts, sands, and phosphates	Semi-confining unit		2
Oligocene	Suwannee limestone	Weathered, fossiliferous limestone	Upper Floridan aquifer		3
Eocene	Ocala limestone	Friable coquina in a matrix of micritic limestone			
	Avon Park formation	Microfossiliferous carbonate			
		Dolomitic-limestone with intergranular evaporites	MCU II	Lower horizontal no-flow boundary	

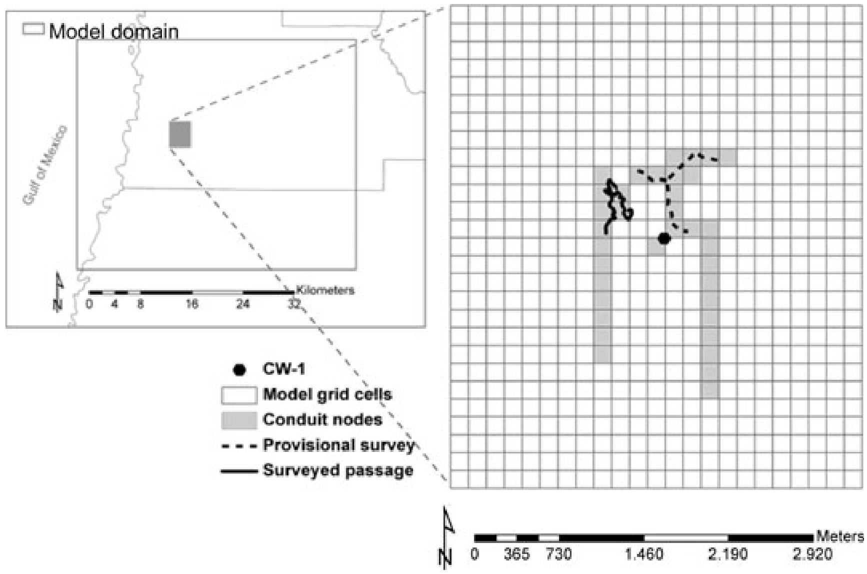

Figure 2. Black lines represent surveyed cave passages. Solid line (SP-2) verified with radiolocation (Hill 2008). Dashed black line (SP-1) is provisional survey data that have not been verified with radiolocation. Gray cells represent conduit nodes, white cells represent matrix. Cave-survey data courtesy of Karst Underwater Research, Inc. (2008b). Note the location of the CW-1 well with respect to the survey data.

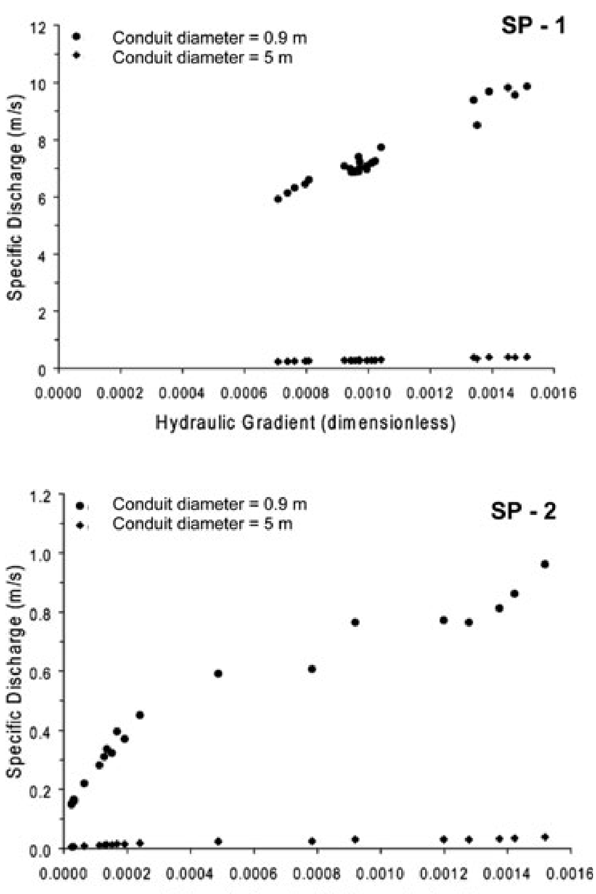

Figure 3. Plots of specific discharge and hydraulic gradient for SP-1 and SP-2 using conduit diameters of 0.9 and 5 m. The deviation from linearity at SP-2 indicates that turbulent flow occurs in the narrower passages underlying SP-2.

occurs in these passages. These findings are corroborated by anecdotal evidence provided by cave divers. Divers describe portions of the flow in the conduit network where constrictions occur as "raging" (Karst Underwater Research, Inc. 2008b). In fact, velocities are so high in the vent at SP-1 during average conditions that divers are unable to enter the underlying conduit network except when flows are abnormally low during drought conditions (Karst Underwater Research, Inc. 2008a). In reality, as conduits widen and constrict, flow likely varies from laminar to turbulent and conversely.

Temporal Variation in the Magnitude and Direction of Fluid Exchange Between the Matrix and Conduit Network

Water level hydrographs for the matrix and conduit network illustrate the response to two local-scale, short-duration (hours) intense convective storm events, A and C and two regional-scale, relatively longer duration (days) tropical storm events, B and D (Figure 4). Locally intense, short-term events did not produce a major response in the matrix or conduit network relative to the regional-scale, multiday storm recharge events in September 2004. Minor responses of less than 0.05 m were observed following the local-scale, short-duration, convective storm events (A and C). Conversely, a larger increase of 0.5 m was observed at MW-2 following Tropical Storm Frances (event B, Figure 4). Water levels continued to increase following Tropical Storm Frances and a relatively shorter duration, (hours) lower volume event (C), before reaching a maximum level approximately a week after the passage of Tropical Storm Frances, with a total water level increase of 0.7 m at MW-2. A water level increase slightly above 0.1 m was observed at MW-2 following passage of Tropical Storm Jeanne (event D, see Figure 4).

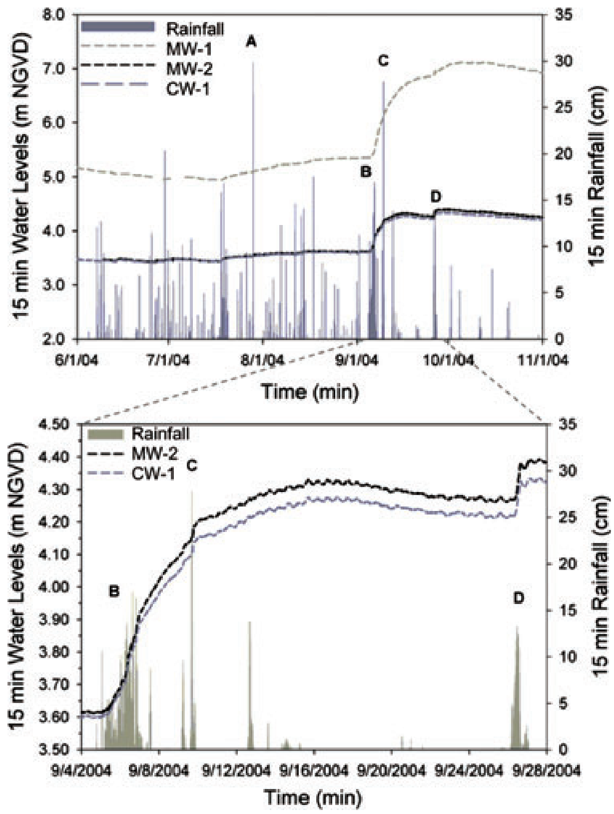

Figure 4. Hydrographs of water levels in the matrix and conduit network vs. rainfall. Rainfall quantities represent total 15-min quantities for the shaded area (132 km^2) shown in Figure 1. Events A and C reflect quantities from convective storms, whereas events B and D reflect quantities from tropical storms. MW-2 and CW-1 are 920 m apart.

Closer inspection of water levels during each storm event at MW-2 and CW-1, which are approximately 920 m apart, indicates that water levels in the conduit network approaches equilibrium with the matrix during events A and B (Figure 5). Water levels in the matrix and conduit network indicate that water levels in the conduit network generally do not exceed those in the matrix during and after these events. Conduit network water levels exceeded those in the matrix only briefly during event A, producing a flux of groundwater from the conduits into the matrix. During the brief reversal, water level differences between the matrix and conduit network were minimal and well within measurement error (i.e., less than 0.03 m). Temperature shifts were also below instrument specifications (i.e., ±0.15°C).

These results are useful for evaluating the performance of CFP Mode 1 and for understanding aquifer response. They indicate that even during longer duration storm events water levels in the matrix generally are higher than water levels in the conduit network at the site, which is also supported by temperature data that remain fairly constant in the conduit well and springs. Although the magnitude of flux between the matrix and conduit well varies temporally, the direction of fluid exchange from the matrix into the conduit network is primarily unidirectional indicating that the conduit network underlying the study area drains the matrix. Water levels in the matrix and conduit network also indicate that the conduit network feeding the springs is not connected to point sources of recharge and that recharge is diffuse. Therefore, direct recharge was not allocated to the conduit nodes in the CFP Mode 1 model.

The observations from the monitoring wells are corroborated by discharge measurements performed at SP-2. Ratios of peak discharges relative to baseflows at SP-1 and SP-2 for these two individual storm events, also referred to as the flashiness of the spring, exhibit what White (1988) and Florea and Vacher (2006) characterize as a slow response.

Our results from the high-frequency monitoring phase are also corroborated by other researchers (Florea and Vacher 2007), who note a similar response following Tropical Storms Frances and Jeanne in caves that do not interact directly with surface-water sources located north and northwest of our site, in Alachua, Marion, and Citrus counties. However, the direction and magnitude of fluid exchange observed in this study differs from previous studies of fluid exchange between the matrix and conduit network in the Upper Floridan aquifer at the Santa Fe Sink/Rise, where shallow conduits interact directly with surface-water sources (Martin and Screaton 2001; Martin and Dean 2001; Martin 2003; Screaton et al. 2004; Martin et al. 2006). One can argue that the separation (920 m) between CW-1 and MW-2 is too large to accurately reveal the differences between conduit and matrix water levels. Indeed, the differences between them are minimal and more frequent reversals are plausible.

Simulated Matrix–Conduit Water Levels

We varied the conduit wall conductance parameter until simulated conduit water levels in the vicinity of CW-1 satisfactorily matched observed matrix water levels at MW-2. Simulated conduit water levels for the conduit model cell with CW-1 relative to the matrix at MW-2 closely mimic each other and have a similar response to that observed during the high-frequency monitoring period shown in Figures 4 and 5. Although MW-2 has a discontinuous record of observed water levels during the low-frequency monitoring period relative to the high-frequency monitoring period shown in Figure 5, the simulated values in the CFP Mode 1 model for both the matrix and conduit water levels agree favorably with observed data. Observed and simulated matrix water levels at MW-2 are predominately higher than observed and simulated water levels at CW-1 (Figure 6).

Simulated Discharges

The CFP Mode 1 model, on average, simulated 89% of observed discharge at the first magnitude spring (SP-1) as compared with 77% simulated in the laminar ECM. Simulated discharges at SP-2 using CFP Mode 1, on average, were 85% of observed values as compared

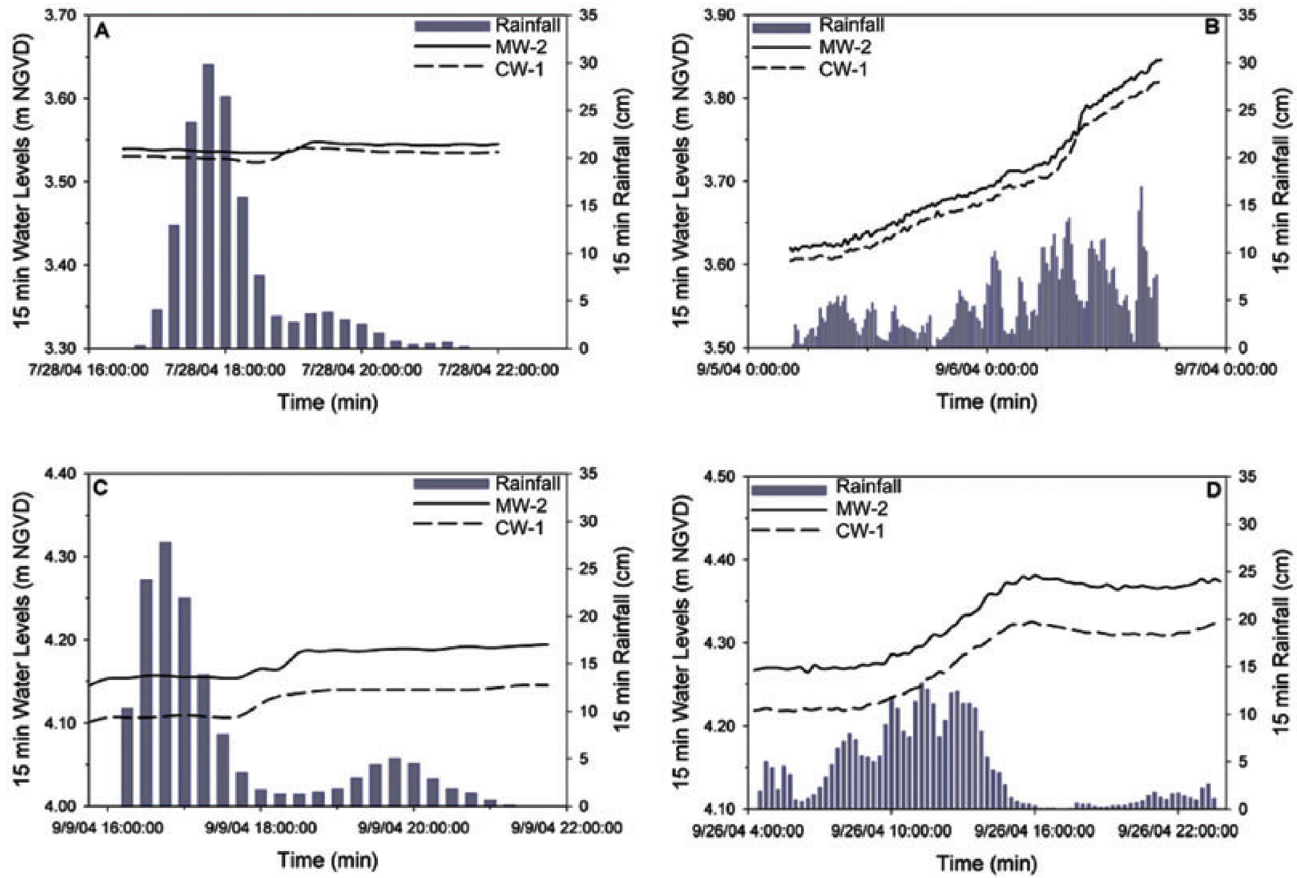

Figure 5. Hydrographs for MW-2 and CW-1 during events A through D. Bar widths represent 15-min rainfall intervals for a 132 km^2 area (shaded area shown in Figure 1).

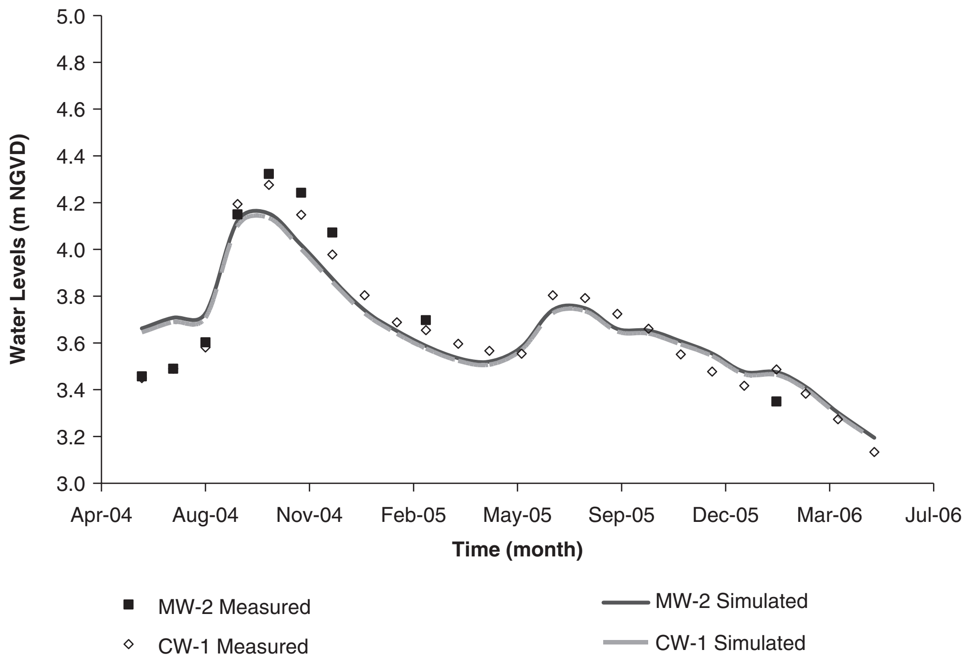

Figure 6. Simulated water levels for the conduit model cell with CW-1 relative to the matrix with MW-2. The simulated responses agree favorably with the observed responses during the high-frequency monitoring period.

with 45% for the laminar ECM. For the first magnitude spring, CFP Mode 1 improved the match between observed and simulated discharges by 12% relative to the ECM using MODFLOW-2005 (Hill et al. 2008). We evaluated the effect of the differences in hydraulic conductivities between the two models by rerunning the ECM using the same hydraulic conductivity array used in the CFP Mode 1 model. Of the improvement, 8% was attributed to decreasing inflated bulk hydraulic conductivities and 4% was attributed to fluid exchange between the matrix and conduit network. Simulated discharges for SP-2, on average, improved 40% with the use of CFP Mode 1. MODFLOW-2005, using the same hydraulic conductivity array used for the CFP Mode 1 model, overestimated discharges at SP-2 during the cessation of flow that occurred during drought conditions relative to CFP Mode 1 (Figure 7). Although discharge at SP-1 is still generally under simulated, CFP Mode 1 produced the closest match between observed and simulated discharges. The match between observed and simulated discharges for SP-1 may have been improved in both models, had we accounted for antecedent rainfall, or the lag time (Knochenmus and Yobbi 2001) in the net recharge estimates. Simulated aquifer water levels and model statistics based on the 32 target wells did not vary significantly between the ECM and CFP Mode 1 models (Table 2). Both models are within normal limits with values of 0.03 for the residual standard deviation divided by the range in target values (Rumbaugh and Rumbaugh 2004).

The sensitivity of laminar and laminar-turbulent flow on simulated discharges at SP-1 and SP-2 was evaluated for the CFP Mode 1 model. This was performed because the plots of specific discharge vs. hydraulic gradient (Figure 3) indicate that laminar and turbulent flow may occur in portions of the conduit network. Simulated discharges using CFP Model 1 differed by less than 1% with laminar flow (Hagen-Poiseuille) or turbulent flow (Darcy-Weisbach) in the conduit network.

Concluding Remarks

Our evaluation indicates that including a parameter that permits fluid exchange between the matrix and conduit network may be a relatively more important parameter than turbulent flow for simulating discharge in karst aquifers, particularly if the objective is to simulate discharge in areas strongly affected by fluid exchange between the matrix and conduit network. We were able to improve the match between observed and simulated discharges by coupling a traditionally sensitive parameter such as hydraulic conductivity with the new conduit wall conductance parameter introduced with CFP Mode 1 that permits fluid exchange between the conduit and matrix network. We observed that strictly laminar flow vs. laminar-turbulent flow in the conduit network did not significantly affect simulated discharges (less than 1%). This finding appears to be supported by previous studies, where improvements between the match for simulated and observed discharges have been observed when flow through the conduit network was strictly laminar. For example, GeoTrans Inc. (1988a, 1988b) note an improvement in simulated discharges using a laminar, finite-element DPM in the vicinity of Rainbow and Silver Springs, in central Florida. Similarly, Mohrlok and Sauter (1997) conclude that a laminar-turbulent discrete model and a comparable laminar dual-continuum model for a

Table 2 **Statistics for the 32 Target Wells in the ECM and CFP Mode 1 Models**					
Model	**Residual Mean (m)**	**Residual Standard Deviation (m)**	**Absolute Residual Mean (m)**	**Range in Target Values (m)**	**Residual Standard Deviation/Range in Target Values**
ECM	0.17	0.98	0.77	28.05	0.03
CFP Mode 1	−0.25	0.97	0.77	28.05	0.03

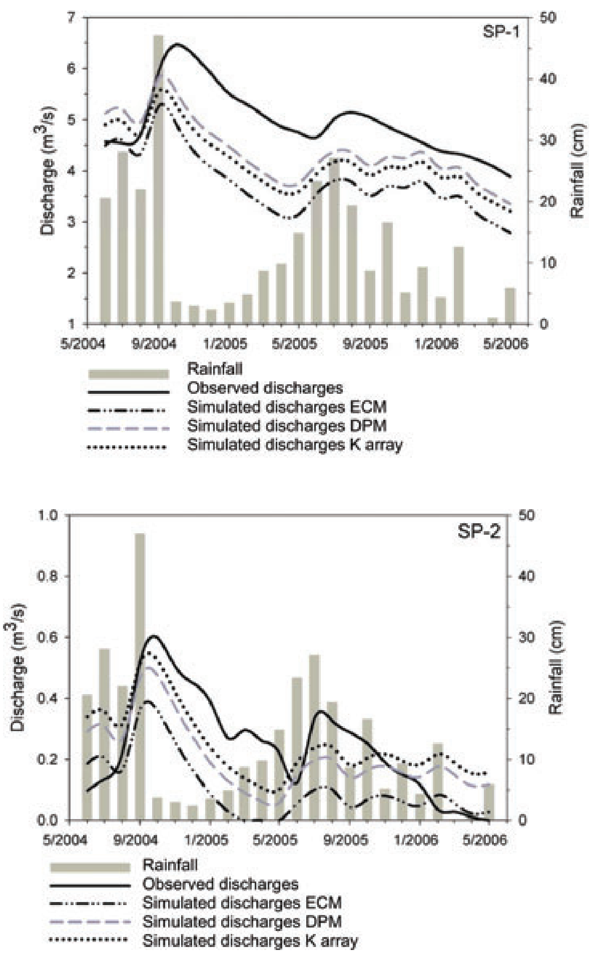

Figure 7. Hydrographs of observed and simulated discharges for the ECM using MODFLOW-2005, the DPM using CFP Mode 1, and the ECM with MODFLOW-2005 using the hydraulic conductivity (K) array originally used for the CFP Mode 1 model.

test site in Swabian Alb, Germany, both adequately match simulated and observed discharges.

Parameter sensitivity may vary by test site and traditionally sensitive parameters such as recharge and hydraulic conductivity remain important (Hill 2008); however conduit wall conductance, a new parameter introduced with CFP Mode 1, did contribute a modest improvement in the match between simulated and observed discharges. Although extensive characterization is required to apply CFP Mode 1, these data are useful for understanding and managing karst aquifers.

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