Performance Evaluation of the MODFLOW-2005 Conduit Flow Process Applied to a Karst Aquifer Underlying West-Central Florida

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Abstract

The MODFLOW-2005 Conduit Flow Process (CFP) was used to simulate discharge and matrix-conduit water levels in a dual-permeability karst aquifer in the vicinity of Weeki Wachee, west-central Florida. The performance of MODFLOW-2005 with an equivalent continuum model, which simulates only laminar flow, relative to MODFLOW-2005 CFP Mode 1, which simulates both laminar and turbulent flow, as well as fluid exchange between the matrix and conduit networks in a dual-conductivity model, was evaluated. Simulated water levels in the matrix and conduit networks were evaluated by comparing these levels to observed values from monitoring wells penetrating the matrix and conduit networks. Additionally, observed discharge hydrographs following convective and tropical storms, as well as drought conditions, were compared to simulated discharges from transient simulations using MODFLOW-2005 and MODFLOW-2005 CFP Mode 1. Results indicate that the application of MODFLOW-2005 CFP Mode 1, with the dual-conductivity model, improves the overall match between simulated and observed discharges by 12 to 40%. We conclude that the dual-conductivity model, using MODFLOW-2005 CFP Mode 1 is a better tool for simulating discharge from the dual-permeability Upper Floridan aquifer, particularly during periods of low net recharge, than the equivalent continuum model using MODFLOW-2005.

INTRODUCTION

Karst aquifers differ from other porous media aquifers because of the secondary porosity that develops in them as a result of dissolution (Palmer, 1999). Karst aquifers consist of triple porosity that includes: (1) intergranular, (2) fracture, and (3) conduit (or cave) porosities (Palmer, 1999; Worthington et al., 2000; Martin and Screaton, 2001; White, 2002). Intergranular porosity comprises the matrix network, whereas the conduit porosity comprises the conduit network (Palmer, 1999; Worthington et al., 2000; Martin and Screaton, 2001). Fracture porosity can be lumped with either the matrix or conduit network depending on aperture widths (White, 1988; Worthington et al., 2000; Martin and Screaton, 2001). Dual-permeability arises from both the matrix and conduit networks (White, 1999). Groundwater flow in dual-permeability karst aquifers can exhibit both Darcian (laminar) and non-Darcian (turbulent) flow, with Darcian flow generally dominating in the matrix network and non-Darcian flow occurring in the conduit network (Martin and Screaton, 2001). Complicating the understanding of flow in karst aquifers is the head-dependent fluid exchange between the matrix and conduit networks, which is site specific (Bauer et al., 2003; Martin and Screaton, 2001; Martin et al., 2006; Hill, 2008; Hill et al., 2008). Moreover, conduit wall conductance between the matrix and conduit networks is an important parameter for improving the match between observed and simulated discharge in transient simulations during periods of low net recharge (Hill, 2008; Hill et al., 2008).

In this study, we compare the relative performance between a transient, laminar/turbulent, dual-conductivity site-scale model using MODFLOW-2005 CFP Mode 1 (Shoemaker et al., 2008) and a comparable transient, laminar equivalent continuum model using MODFLOW-2005 (Harbaugh, 2005) for the dual-permeability Upper Floridan aquifer in the vicinity of Weeki Wachee, west-central Florida, fig. 1. The purpose of this article is to present the results of the model performances.

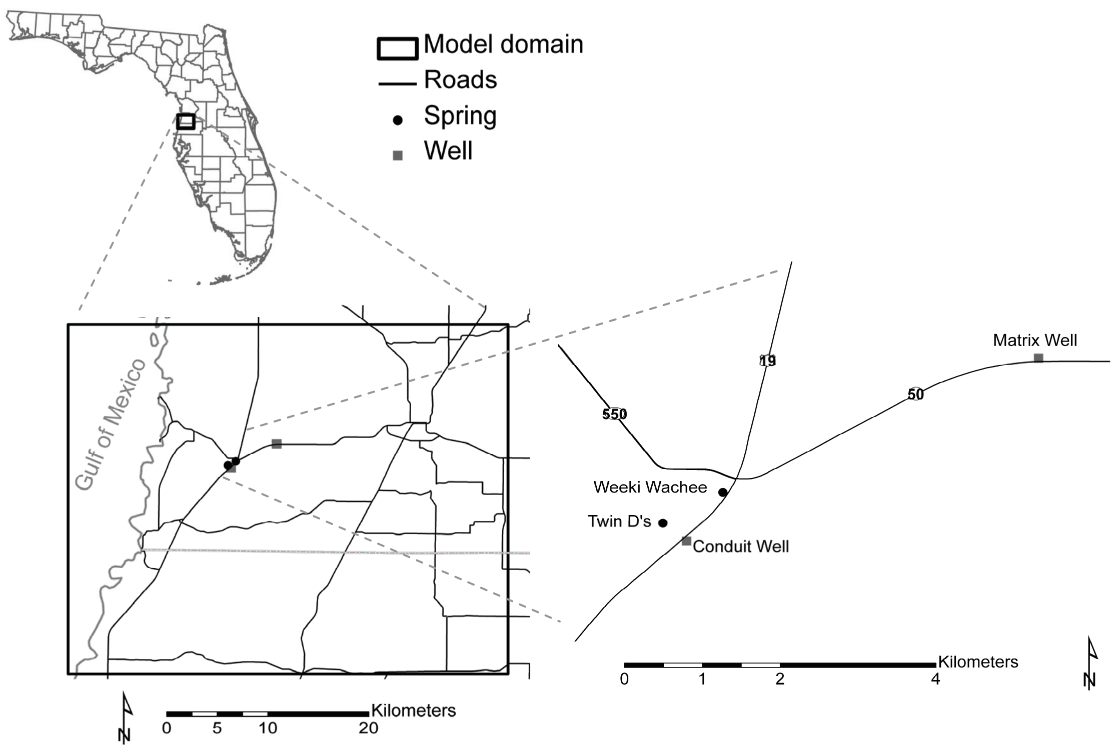

Figure 1. Site and location map with springs and monitoring wells.

STUDY AREA

The dual-permeability Upper Floridan aquifer underlies the study area. The Upper Floridan aquifer is composed of soluble Oligocene and Eocene carbonates and varies from unconfined to semi-confined conditions. The Upper Floridan aquifer comprises the Suwannee Limestone, Ocala Limestone, and Avon Park Formation, in descending order (Miller, 1986). Throughout the study area, a thin mantle varying from less than a meter to 61 m in thickness blankets the Upper Floridan aquifer (Hill, 2008). Springs, sinkholes, and underwater caves are present throughout the study area. Multiple episodes of karstification resulted during the Cenozoic Era in response to sea level fluctuations (Florea et al., 2007). Sea level fluctuations coupled with possible former mixing zones (Reeder and Brinkmann, 1998) produced large, horizontal elliptically shaped conduits sub-parallel to depositional layers, circular chambers, and vertical elliptically shaped conduits normal to depositional layers. Passage widths can exceed 15 m at Weeki Wachee Spring and at the outermost mapped portions of Twin D's Spring (Southwest Florida Water Management District, 2001; Karst Underwater Reseach, Inc., written communication, 2008).

STUDY APPROACH

A site-scale laminar equivalent continuum model using MODFLOW-2005 and a comparable laminar/turbulent, dual-conductivity model using MODFLOW-2005 CFP Mode 1 were developed for the study area. The models consist of uniform grids with 285 columns and 236 rows. Cell widths are 152 m. The transient models consist of 24 stress periods spanning from June 2004 through May 2006. Observed discharges and water levels in monitoring wells penetrating the matrix and conduit networks during the 2-year period span extreme hydrologic conditions including 2 wet and dry seasons (Jordan, 1984) passage of Tropical Storms Frances and Jeanne (fig. 2) in September 2004 and a cessation of flow at Twin D's Spring in May 2006 (Hill, 2008; Hill et al., 2008; Reimann and Hill, 2008).

Conduits were explicitly incorporated into the dual-conductivity model using cave-survey data provided by Karst Underwater Research, Inc., written communication, 2008. Parameters were kept constant between the transient equivalent continuum and dual-conductivity models with the exception of hydraulic conductivity, the conduit wall conductance that permits fluid exchange between the matrix and conduit networks, and the upper and lower Reynolds numbers (Reimann and Hill, 2008). Conduit wall conductance was constrained using observed data (Hill, 2008; Hill et al., 2008). Conduit wall diameters were constrained using descriptions provided by cave divers (Southwest Florida Water Management District, 2001; Karst Underwater Research, Inc., written communication, 2008).

Model performance was evaluated in terms of the match between observed and simulated discharges and water levels for monitoring wells penetrating the matrix and conduit networks, fig. 1. Discharge from two springs, Weeki Wachee, a first magnitude (≥ 3 m3/s) spring Meinzer 1927; Scott et al. 2004, and Twin D's, locally referred to as Little Spring, or Twin Dees, Scott et al. (2004), a spring that under average flow conditions from, June 2004 through May 2006, was a third magnitude (≤ 0.3 m3/s) spring (Meinzer, 1927; Hill, 2008; Hill et al., 2008). During that period, flow occasionally exceeded 0.3 m3/s at Twin D's Spring (second magnitude) (Meinzer, 1927; Hill, 2008; Hill et al., 2008) during high recharge events. Both springs discharge fresh water (Southwest Florida Water Management District, 2001).

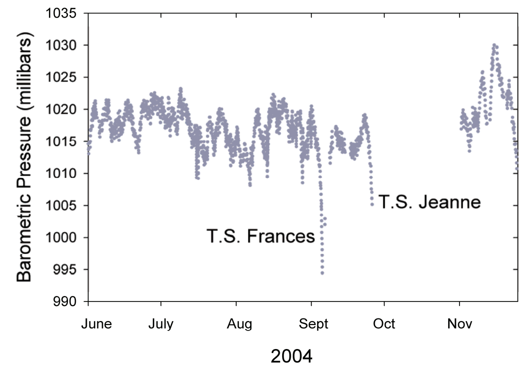

Figure 2. Hourly barometric pressure data from a National Oceanographic and Atmospheric Association (NOAA) station located 12 km from Weeki Wachee. Note the decrease in barometric pressure with passage of Tropical Storms (T.S.) Frances and Jeanne. Gaps represent missing data.

PERFORMANCE OF MODFLOW-2005 CFP MODE 1 RELATIVE TO MODFLOW-2005

The dual-conductivity model using MODFLOW-2005 CFP Mode 1 matched observed and simulated discharges more closely, particularly during low net recharge periods, compared to the equivalent continuum model using MODFLOW-2005 (fig. 3). Simulated discharges for Weeki Wachee Spring using the dual-conductivity model were on average 89% of observed values as compared to 77% using the equivalent continuum model. Simulated discharges for Twin D's Spring using the dual-conductivity model were, on average, 85% of observed values as compared to 45% using the equivalent continuum model. Application of MODFLOW-2005 CFP Mode 1 with the dual-conductivity model resulted in an overall improvement of 12 to 40% in the match between observed and simulated discharges. Although a percentage of the increase in simulated discharges was attributed to decreases in bulk hydraulic conductivities, some of the improvement was attributed to fluid exchange between the matrix and conduit networks (Hill, 2008; Hill et al., 2008; Reimann and Hill, 2008). Simulated water levels in the conduit and matrix wells did not differ significantly from each other in the equivalent continuum and dual-conductivity models as seen in figure 3 (Hill, 2008; Hill et al., 2008; Reimann and Hill, 2008).

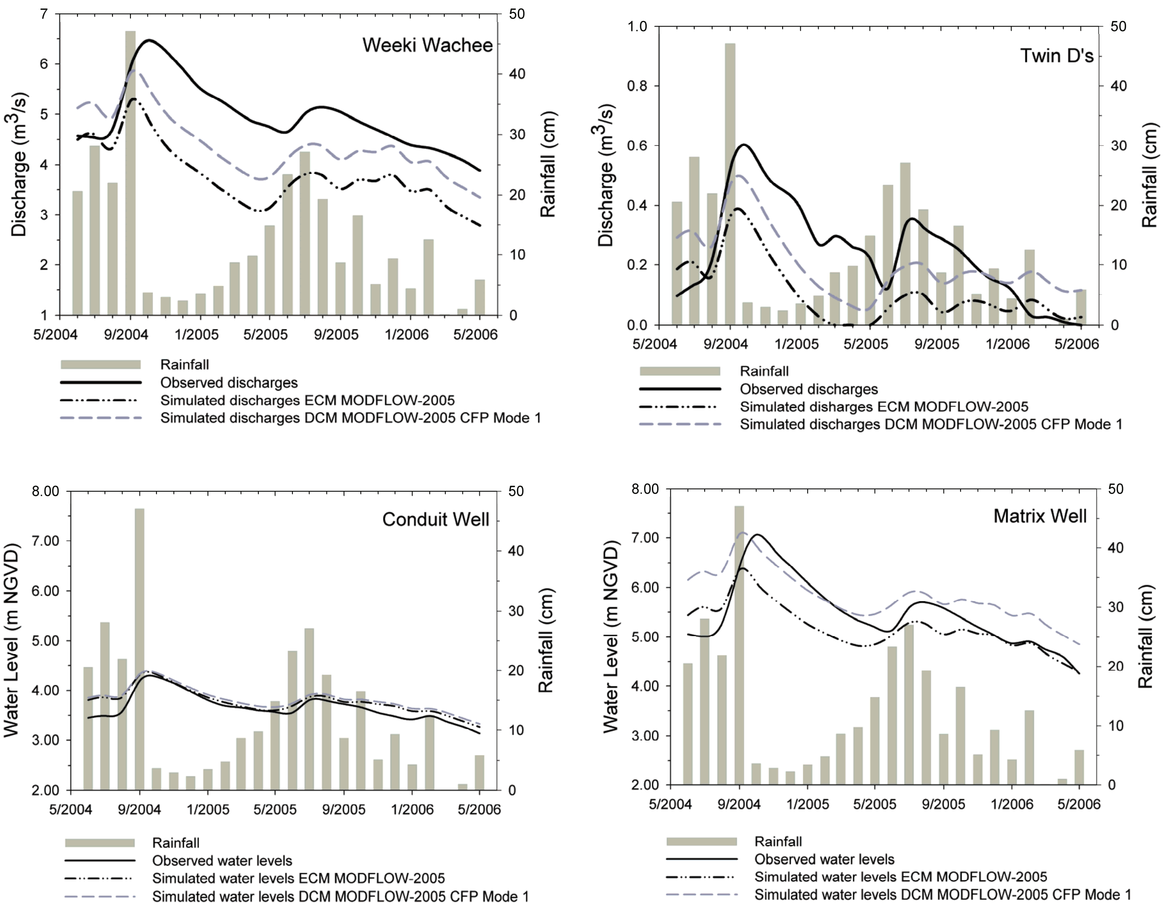

Figure 3. Plots of observed and simulated discharges at Weeki Wachee and Twin D's Springs for the laminar equivalent continuum model (ECM) using MODFLOW-2005 and the laminar/turbulent dual-conductivity model (DCM) using MODFLOW-2005 CFP Mode 1. Average monthly rainfall quantities are for a 132 km2 area. Rainfall estimates provided by OneRain, Inc. and consist of Doppler radar distributions coupled with rainfall quantities calibrated using rainfall gauges (Hoblit and Curtis, 2005). Note the increase in discharge and water levels during September 2004 with passage of Tropical Storms Frances and Jeanne and the cessation of discharge in May 2006 at Twin D's Spring. Caliper or video logs were used to determine if wells monitor the matrix or conduit networks. The conduit well intercepts an underwater cave with a height of approximately 8 m (Hill, 2008; Hill et al., 2008).

SUMMARY AND CONCLUSION

The performance between a transient dual-conductivity model using MODFLOW-2005 CFP Mode 1 and a comparable transient equivalent continuum model using MODFLOW-2005 was evaluated in the vicinity of Weeki Wachee, west-central Florida. The study area is underlain by the dual-permeability Upper Floridan aquifer. The models spanned extreme hydrologic conditions that included high recharge events associated with tropical storms and a drought that included a cessation of flow at Twin D's Spring.

Results obtained during these simulations indicate that the dual-conductivity model using MODFLOW-2005 CFP Mode 1 performed better than the equivalent continuum model using MODFLOW-2005. A better match between observed and simulated discharges during extreme hydrologic conditions was obtained with MODFLOW-2005 CFP Mode 1. These results indicate that the dual-conductivity model using MODFLOW-2005 CFP Mode 1 is a better tool for simulating discharge in the dual-permeability Upper Floridan aquifer during periods of low net recharge, relative to the equivalent continuum model that considers the bulk properties of the matrix and conduit networks. This conclusion particularly applies near areas of focused discharge where fluid exchange is present between the matrix and conduit networks.

ACKNOWLEDGEMENTS

The authors gratefully thank W. Barclay Shoemaker of the USGS for providing the MODFLOW-2005 Conduit Flow Process. We also thank Karst Underwater Research, Inc. for providing the cave survey data. This study was partly funded by the Southwest Florida Water Management District.

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