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Short Communication

Study on groundwater flow and salinity distribution cycling controlled by seawater/freshwater interaction in Woodville Karst Plain, Florida, USA

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ABSTRACT

Seawater intrusion due to sea level rise and climate change could significantly damage coastal groundwater resources, in Florida, the flattest state in the US. Based on field observation and measurement, a three phase conceptual model was proposed for describing seawater and fresh water interaction at Woodville Karst Plain(WKP), Florida, a typical karst system in the Floridan aquifer. Then, a numerical model is developed to quantitatively investigate the groundwater flow cycling and seawater intrusion to the groundwater system. The karst conduit network in the aquifer acts as fast flow pathways for groundwater flow and solute transport, which allows seawater deeply intrude the aquifer. Wakulla Spring, an inland spring 11 miles from the coast and the coastal submarine spring, Spring Creek Spring Complex are connected through the conduit network. The flow direction between the two springs varies due to rainfall condition in the region, thus the discharges at two karst springs are used to estimate the location of seawater/freshwater mixing interface. The salinity distribution and seawater intrusion to the conduit system are very sensitive to precipitation variation. Furthermore, predictions are made for sea level rise and hurricane event with extreme precipitation scenarios. The results show that the seawater could intrude to the inland spring and contaminant the fresh water system if sea level rise 1.0 m. A large area of the aquifer would be contaminated in a long-term dry season.

Introduction:

Karst carbonate rock has relatively large void spaces and loose porous medium structure that contains large amount of groundwater resource, usually becomes a regional aquifer, such as the Floridian aquifer in Florida and south parts of Georgia, Alabama and South Carolina reported that karst bedrocks encompass about 10-20% of the Earth's landmass, supply drinking water for nearly 25% of the world's population. Complex sub ground conduit systems usually can be found in a karst aquifer due to long-term carbonate dissolution in joints and fractures. Hydraulic characteristics of a rapid non-laminar even turbulent flow in conduit networks could be significant different from those of a slow Darian flow in a porous medium. As a result, dual permeability or even triple permeability characteristics including porous medium, fractures and conduits, control groundwater flow patterns in a well-developed heterogeneous karst aquifer. Although most groundwater resource in a karst aquifer is stored in carbonate matrix pores, groundwater flow is mainly through the conduit system. Rapid water flows in conduits and dynamic water exchanges between conduits and surrounding rocks accelerate the groundwater residence time, which is important to groundwater contamination as well as seawater intrusion in coastal area. Contaminants contained in conduits can be pushed into the carbonate matrix when water pressure in a conduit is higher than that in its surrounding matrix during high-flow events. During low-flow events, contaminants flow from matrix back into the conduit when pressure difference reverses. Groundwater contamination as well as seawater intrusion in a karst aquifer can persist for a long time because of matrix retention and dynamic exchange.

Sea level rise has been recognized as one of the most threatened environmental issues world-widely because of global warming and climate changes. The rising sea level not only inundates cities and farmlands on the shore, but also contaminates fresh groundwater resource through seawater intrusion in a coastal aquifer. According to a slight sea level rise would move the mixing interface significantly further landward in an aquifer. In a karst coastal aquifer with well-developed conduits, seawater could fill in the submarine caves and intrude much further through the high permeable conduits. Davis and Verdi reported the flow discharge rate at an inland karst spring significantly increased in the last century. A historical data of rising sea level at the Gulf of Mexico is believed to be an important reason that affects the inland spring's discharge through submarine caves and extended conduit networks. The effects of sea level rise on the groundwater flow cycling and regional flow field in the aquifer was predicted and quantitatively evaluated in this study.

Many numerical dual-permeability models have been developed to study groundwater flow and solute transport in karst aquifers with well-developed conduits and developed a limestone dissolution continuum model coupled with conduit flow to simulate karst evolution and groundwater flow in a karst aquifer. A numerical model for groundwater flow in a karst aquifer by coupling three-dimensional laminar groundwater flow in porous medium with turbulent flow in a karst conduit. It used two-dimensional pipe networks to simulate the processes of conduit development under laminar flow conditions at field scales. Later on, the simulation method was extended to turbulent. Simulations of conduit evolution were conducted from random, two-dimensional fractures in a karst aquifer coupled a pipe network with a continuum system to study karst development processes. Their study results indicate the early certification might be enhanced by the presence of a diffuse flow system.

Hybrid discrete-continuum model coupled discrete pipe flow with continuum porous medium flow has been verified to be an appropriate approach to simulate groundwater in a karst aquifer developed the CAVE code, which is a discrete-continuum model to simulate non-laminar pipe flow coupled with darcian flow in continuum matrix domain. The model was and further extended developed the CFP packages for MODFLOW-2005 based on the previous works, which has been applied and evaluated in a number of studies Recently, MODFLOW-CFP to simulate unsaturated flow in conduits and water exchange between matrix and partial filled conduits. Furthermore, conduit associated drainable storage and time-variable boundary condition was added in MODFLOW-CFPM1. Based on these studies, a research version of CFPv2 has been developed and used in this study.

Based on the springs' discharges, surface water recharges, salinity at Spring Creek Springs and precipitation data in the WKP from June 2007 to June 2010, a conceptual model of three repeating phases for the groundwater interactions among Spring Creek Springs, Wakulla Springs and Lost Creek. In phase 1, seawater backflows into the conduits at Spring Creek Springs with high salinity and very low freshwater discharge during an extended low rainfall period. Freshwater discharge is blocked at Spring Creek Springs by higher-density seawater and diverted to Wakulla Springs. Phase 1 switches to phase 2 after a heavy rainfall event resulting from temporarily high inflows from sinkholes to groundwater that purge seawater out of the Spring Creek Springs submarine conduits. Discharges of both springs increase dramatically in this phase, especially at the submarine springs. Phase 2 transforms to phase 3 when a low rainfall period returns. Surface water recharge returns to baseflow condition, but the submarine springs remain large quantity of freshwater discharge coming from groundwater storage; therefore, salinity is still low at the submarine spring.

In this study, CFPv2 was applied instead of MODFLOW-CFP to simulate the seawater and groundwater interaction processes since MODFLOW-CFP is not applicable to a time dependent boundary condition in the numerical model. The CFPv2 model is setup to numerically represent the conceptual model of the groundwater flow cycling in the Upper Floridian Aquifer (UPA) of Woodville Karst Plain, north Florida, USA. The modeling study focuses on the impacts of precipitation, surface water recharges and hydraulic head variation caused by seawater intrusion at Spring Creek Springs on springs' discharge and groundwater flow cycling. The rest of the paper is arranged as: the hydrological characteristics of the Woodville Karst Plain (WKP), the Upper Floridan Aquifer (UPA), and the springs including Wakulla Springs and Spring Creek Springs are introduced in part 2. The governing equations, numerical methods, data collections are presented in part 3. The model implementations, numerical simulation results and prediction of sea level rise are provided in part 4. The discussion and conclusion including the uncertainties and impacts on seawater intrusion are made in part 5.

Conclusion:

Numerical CFPv2 groundwater modeling in this study provides a quantitative description of groundwater flow cycling and discharges at Spring Creek Springs and Wakulla Springs from June 2007 to June 2010, based on the three-phase conceptual model for groundwater interaction in the WKP. Conduit flow could be non-laminar even turbulent, so Darcy's Law as well as the MODFLOW code for groundwater flow in porous medium are no longer appropriate to describe groundwater flow. A modeling method for density-dependent flow in a karst aquifer with conduits is developed and used to simulate groundwater flow cycling in the Woodville Karst Plain in this study. Complex interactions between seawater, freshwater and recharges in a dual permeability karst aquifer are numerically simulated by a discrete-continuum CFPv2 model. In general, the simulation results reasonably match the field observations and verify the relationship between the discharges at submarine springs.