Effects of Antecedent Hydrogeologic Conditions on Flood Magnitude and Recharge to the Floridan Aquifer in North-Central Florida

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Groundwater and surface water exchange is poorly quantified in karst aquifers. Consequently, groundwater and surface water elevations were compiled for rivers in north-central Florida and from wells drilled to the lower Floridan Aquifer between January 2000 and 2010 to assess effects of antecedent conditions on flood magnitudes and aquifer recharge during flooding. Floods that occurred when groundwater elevation was higher than average (i.e., "wet" floods) were greater than floods that occurred when groundwater elevation was less than average (i.e., "dry" floods). Excess flooding resulted during wet floods from elevated groundwater levels. More aquifer recharge occurred during dry floods than wet floods because lower water levels provided storage. Flood water may be contaminated, depending on land use, and thus dry floods carry a greater risk of aquifer contamination than wet floods. These relationships between antecedent surface water conditions, storage space, and recharge should improve model prediction of flood magnitude and associated risk of contamination to the Floridan Aquifer System as well as other karst, and possibly non-karst, aquifers.

INTRODUCTION

Water is one of our most important resources. Both surface water and groundwater are used by humans for drinking, irrigation, transportation, entertainment, and are a major service for ecosystems. Almost all surface water features, such as streams, rivers, and lakes, interact with groundwater by exchanging water between these two reservoirs. Surface water can become polluted depending on land use. It may also exchange with groundwater and cause degradation of groundwater quality. Contaminated groundwater can also degrade pristine surface water when it returns to the surface, for example at springs. Thus, an understanding of the interactions between groundwater and surface water is required for effective water management.

One of the most productive aquifers in the world is the Floridan Aquifer, a large karst aquifer. Karst aquifers have high permeability over large scales, which allows for fast exchange between surface water and groundwater (Kincaid et al., 1997). Many karst aquifers form in extensively cemented and recrystallized Mesozoic and Paleozoic carbonate rocks (White, 1969; Smart et al., 1986; Ford et al., 1989). The Floridan Aquifer formed in Cenozoic rocks and thus retains much of its primary porosity, a characteristic referred to as eogenetic (Vacher and Mylroie, 2002). Flow through the primary porosity of the matrix rocks within eogenetic aquifers can be orders of magnitudes faster than within the low porosity matrix rocks of older aquifers (Vacher and Mylroie, 2002). Contamination may be more common in eogenetic karst systems, like the Floridan Aquifer, because of extensive exchange between surface water and groundwater.

The processes controlling exchange between surface water and groundwater are not fully understood (Winter et al., 1998). One possible control on the magnitude of the exchange between surface water and groundwater, and associated influx of contaminants to the groundwater, is the elevation of groundwater relative to surface water. Elevations of both surface water and groundwater may change rapidly or over long periods of time depending on rainfall, flooding, and droughts, and these two elevations may not change in concert with each other. Consequently, we assess how exchange of surface water and groundwater is controlled by variations in water levels in the Floridan Aquifer and estimate the magnitude of recharge of water to the Floridan Aquifer during flooding.

BACKGROUND

Overview of Florida Geology

Scott (1992) described the Florida stratigraphy as a thin top layer of siliciclastic sediment, underlain by thick sequence of carbonate rocks. The carbonate rocks underlie much of the southeastern US, including all of Florida (Figure 1) (Miller, 1997). The stratigraphy of Florida is comprised of rocks that range in age from Paleocene (55 mya) to Late Pleistocene (<100ky) (White, 1970). Deposition was influenced by fluctuations of sea level and alternating subaerial and submarine conditions (Scott, 1992). Carbonate sediment deposition dominated until the end of the Oligocene Epoch (24 mya), and these rocks now form the Floridan Aquifer System (Scott, 1992). The carbonate sediments that make up the Floridan Aquifer System range in thickness from 610 m in northern Florida to 1500 m in southern Florida. The Floridan Aquifer contains numerous conduits, which gives it a high hydraulic conductivity (White, 1970).

Miocene sediments overlying the carbonate aquifer are silts and clays that make up the Hawthorn Group. The Hawthorn Group confines most of the Floridan Aquifer, except where it is less than 30 m thick or missing in northwestern peninsular Florida. Where the Hawthorn Group is missing, the Ocala Formation or the Oligocene Suwannee Limestone, where present, crop out at the surface. The boundary between the confined and unconfined portion of the Floridan Aquifer is a marine terrace that represents the erosional edge of the Hawthorn Group rocks (Scott, 1992). This feature is called the Cody Scarp (Hunn and Slack, 1983) and trends northwest to southeast through north-central Florida (Figure 1).

Surface water is common east of the Cody Scarp, but west of the Cody Scarp surface water is confined to two major rivers, the Suwannee and Santa Fe rivers. Water in these rivers exchanges with groundwater at numerous sinkholes and springs (Figure 1). Although springs typically discharge water, when elevations of the rivers exceed the hydraulic head of the springs they may reverse (Gulley et al., 2011), allowing surface water to flow into the aquifer. Thus, the properties of the Floridan Aquifer, including primary porosity, numerous springs, and a partially confined aquifer, allow extensive exchange of surface water and groundwater.

METHODS

Study Sites

This project focuses on the Suwannee and Santa Fe rivers and uses two example sites on each river in north-central Florida. The Suwannee River is about 430 km long and extends through southern Georgia and north-central Florida, while the Santa Fe River runs 120 km east to west across north-central Florida (Figure 1). The Suwannee Basin drains over 26,000 km^2, and the Santa Fe Basin drains over 3,500 km^2 (Hunn and Slack, 1983). Many tributaries flow into both the upper Suwannee and Santa Fe rivers off the confining unit, giving them an intricate geomorphology (Katz et al., 1997). The main tributaries of the Suwannee River are the Okefenokee Swamp, the Little River, the Alapaha River, the Withlacoochee River, the Santa Fe River, and over one hundred springs (EPA, 2009). The main tributaries to the Santa Fe River are the Ichetucknee and New Rivers and over thirty-six springs.

Six gauging stations on the Suwannee River were used in this study. Specific examples are shown from two gauging stations: Ellaville (site # 02319500) and Dowling (site # 02319800). These sites were chosen due to their well representation of the sites along the Suwannee River. Three gauging stations on the Santa Fe River were used in this study. Specific examples are shown only from sites Worthington (site # 02321500) and Fort White (site # 02322500) due to their well representation of the Santa Fe River. In the Suwannee, most upstream river flow is surface drainage of wetlands and local surficial aquifers (Figure 1). Along the Santa Fe River, most flow upstream from the River Sink is from surface drainage of wetlands. For both rivers, water is tannin rich with high dissolved organic carbon concentration (DOC) if most of the water is from surface runoff, particularly during floods. Water composition is clearer with lower DOC concentrations if the majority of water is from springs, for example during droughts and baseflow.

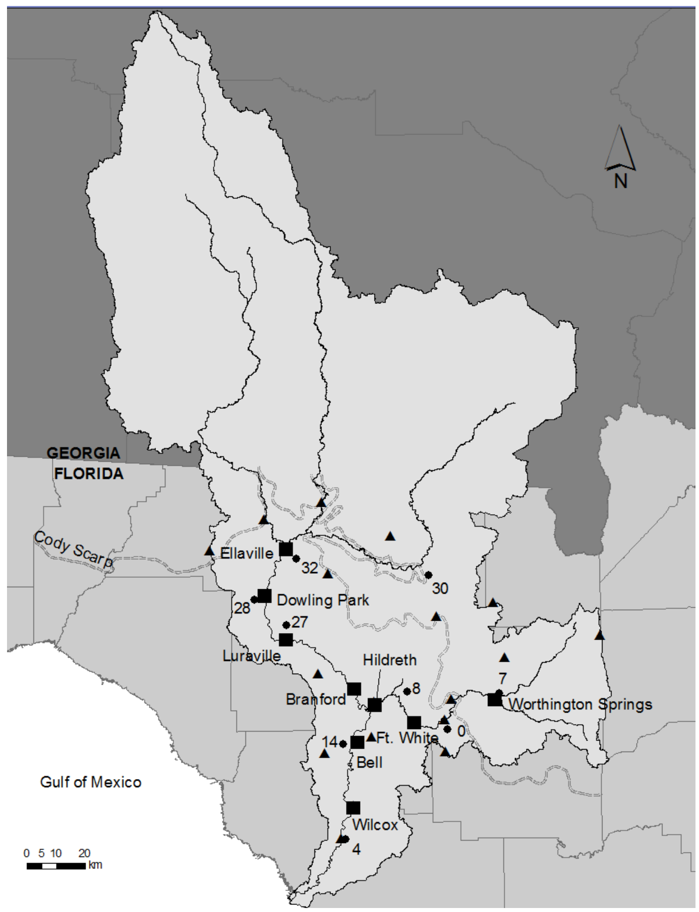

Figure 1. Location map of the Suwannee and Santa Fe river watersheds. Wells are numbered dots, gauging stations are labeled squares, and rain stations are triangles. The dashed line shows the Cody Scarp representing the boundary of confined and unconfined aquifer (SRWMD, 2010).

Data Compilation and Analyses

Stream flow, groundwater, precipitation, and water quality data were compiled from three sources: the Suwannee River Water Management District (SRWMD), the National Water Information System (NWIS), and the

Florida Automated Weather Network (FAWN). The Suwannee River Water Management District maintains most data available from the Suwannee River Basin. Well levels (head values) are collected monthly by the SRWMD, which maintains a database that we accessed for information from wells along the Suwannee River and the Santa Fe River (Figure 1). Wells closest to the river gauging stations (within 5 km) were used in this study. The NWIS database is a national and statewide database maintained by the United States Geological Survey (USGS). Daily discharge and stage heights were compiled from the NWIS database for all river gauging stations along the Suwannee and the Santa Fe rivers (Figure 1). The FAWN database is maintained by the University of Florida-IFAS extension. Daily precipitation and evapotranspiration values were compiled from fourteen counties around the Suwannee and Santa Fe basins. These data were averaged separately for the Suwannee River Basin and the Santa Fe River Basin (Figure 1). Although data is available from some gauging stations as far back as the 1920s, this project focuses on the last ten years to provide the widest possible geographic coverage with a continuous record of flow and water levels. The period of record for all data is from January 1, 2000 – January 1, 2010.

The compiled data were used to define several variables that describe the hydrologic characteristics of the basin. These variables include magnitude of rainfall, estimates of groundwater levels prior to flooding, and differences in discharge between neighboring gauging stations along the river. Magnitude of rainfall events were defined by P-ET value defined as:

$$\textbf{P-ET = Precipitation – Evapotranspiration} \quad \text{(eq. 1)}$$

Rainfall events were considered large if P-ET was above the 99th percentile. Magnitude of antecedent groundwater conditions, H_{GW}, was defined as

$$H_{GW} = \frac{H_{monthly}}{H_{mean}} \quad \text{(eq. 2)}$$

where $H_{monthly}$ is the groundwater head value during a particular month and H_{mean} is the mean groundwater head values for the 10-year period of the study. If the H_{GW} was > 1, then the flood was deemed as wet and if the H_{GW} was < 1, it was deemed as dry.

The magnitude of recharge was determined using the difference in discharge between upstream and downstream gauging stations, Q_{diff} defined as

$$Q_{diff} = \left[\frac{Q_{peak}}{Q_{mean}}\right]_{Upstream} - \left[\frac{Q_{peak}}{Q_{mean}}\right]_{Downstream} \quad \text{(eq. 3)}$$

where Q_{peak} is the highest daily discharge during a flood and Q_{mean} is the mean discharge over ten years. Cross correlation were computed at each site to assess relationships between discharge and groundwater levels, where zero lag shows the strongest correlation between discharge and groundwater. Q_{diff} was compared to the H_{GW} in order to estimate the magnitude of water lost to the aquifer.

Floods were defined as any discharge above 75th percentile of flow. Flood magnitude was determined using the calculated ratio of discharge to P-ET

$$M_{flood} = \frac{Q_{flood}}{P\text{-}ET_{flood}} \quad \text{(eq. 4)}$$

where M_{flood} is the flood magnitude (m^2/s), Q_{flood} is the peak discharge during a flood event (m^3/s), and P-ET is derived from eq. 1. Flood recharge is assumed to occur when upstream site discharge is greater than downstream discharge, thus flood recharge, R_{GW} (m^2), was determined between two sites along a river by

$$R_{GW} = \frac{(Q_{upstream} - Q_{downstream})\, t_{elapsed}}{x} \quad \text{(eq. 5)}$$

$t_{elapsed}$ is the amount of time the discharge exceeded the 75th percentile (s), $Q_{upstream}$ and $Q_{downstream}$ are the discharge during a flood upstream and downstream (m^3/s) summed over $t_{elapsed}$, and x is the distance between the two consecutive sites (m).

RESULTS

Flooding

Large P-ET events do not always produce a flooding event. Large rain events (P-ET > 99 percentile) occurred 30 times within the Suwannee River watershed during the period of study (Figure 2), but only seven of these events corresponded to flood events greater than the 75th percentile. Along the Santa Fe River, over 25 large rain events occurred, but only seven corresponded to flood events greater than the 75th percentile. The largest flood events corresponding to large P-ET events along the Suwannee River, in order of largest to smallest, were September 2004, March 2008, April 2009, March 2003, July 2005, April 2005, and February 2006 (Figure 2). The largest P-ET flood events along the Santa Fe River, in order of largest to smallest, were September 2004, August 2008, April 2009, March 2005, March 2003, June 2003, and July 2005 (Figure 2).

Floods occurred during both large and small P-ET events, but some large P-ET events did not produce large flood events while some small P-ET events did produce large flood events (Figures 2 and 3).

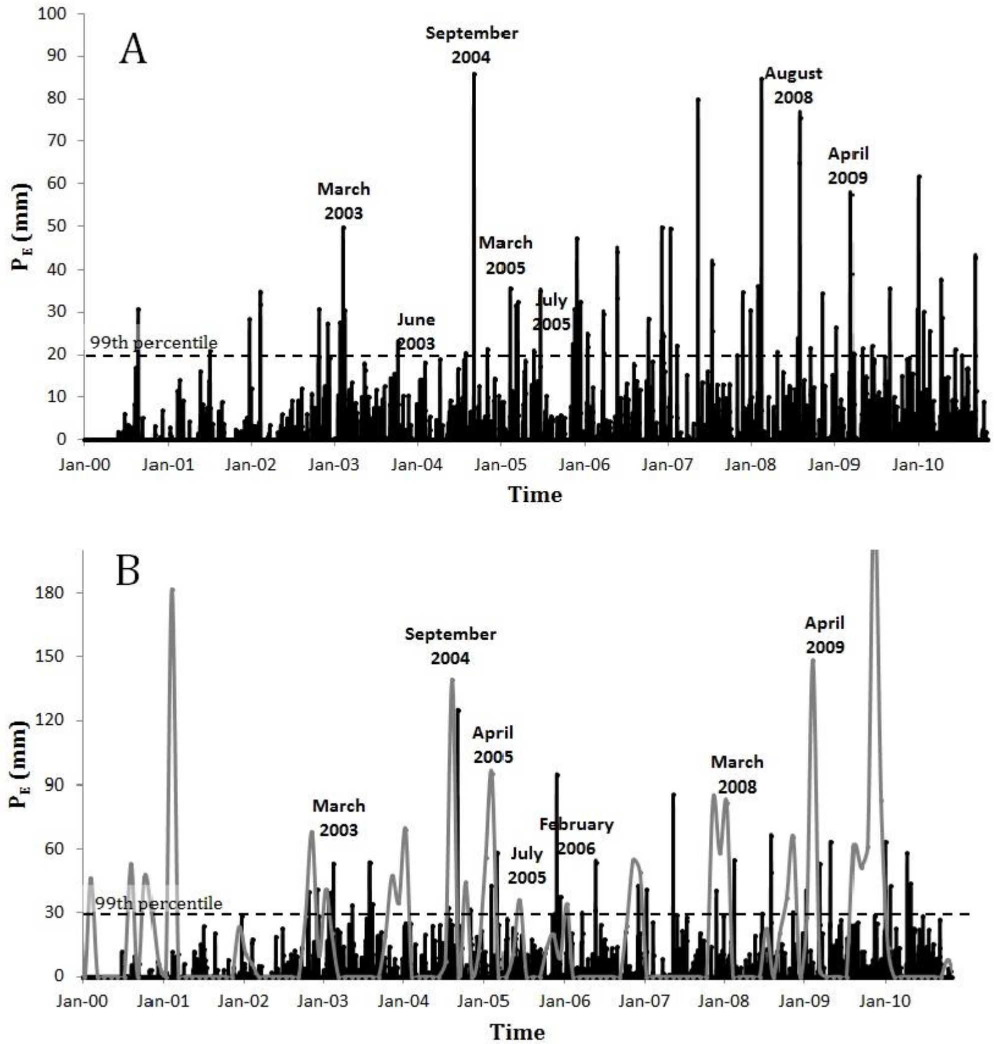

Figure 2. Daily P-ET versus time for A) the Santa Fe River Basin and B) the Suwannee River Basin. Graphs A and B show the numbered P-ET events that correspond to elevated discharge on the Suwannee and Santa Fe rivers. P-ET events were numbered according to decreasing amount of P-ET.

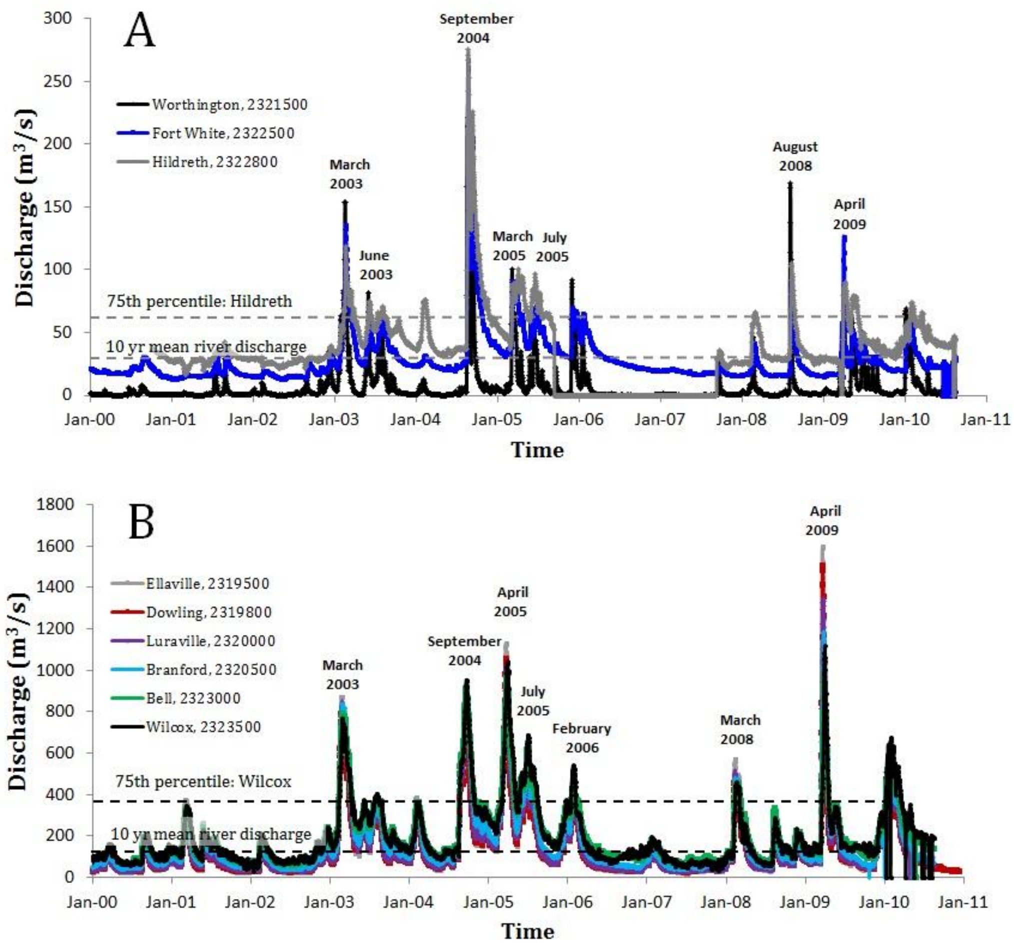

Figure 3. Daily discharge compared to time for A) Santa Fe River and B) Suwannee River. Graphs A and B show the exact flood events that correspond to the elevated P-ET events shown in Figure 2.

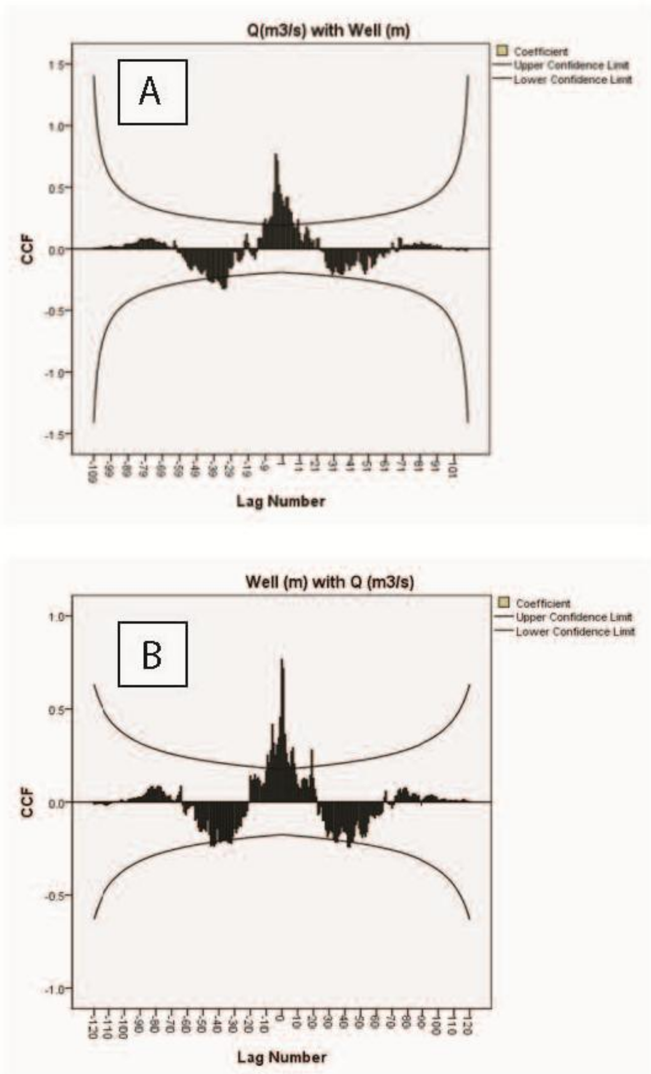

Figure 4. Cross correlation plots of well level vs. discharge for A) Luraville gauging station and well 27 groundwater and B) Fort White gauging station and well 0 groundwater. The strong correlation at zero lag implies that exchange between groundwater and surface water occurs within the one month lag period.

On average, the Santa Fe River had lower M_{flood} values than the Suwannee River (Figure 5). We found that during dry floods, Suwannee's average M_{flood} value was 0.013 m^2/s and Santa Fe's average M_{flood} value was 0.002 m^2/s. In contrast, during wet floods the M_{flood} values increased by 39% for the Suwannee River to 0.018 m^2/s and by 100% for the Santa Fe River to 0.004 m^2/s.

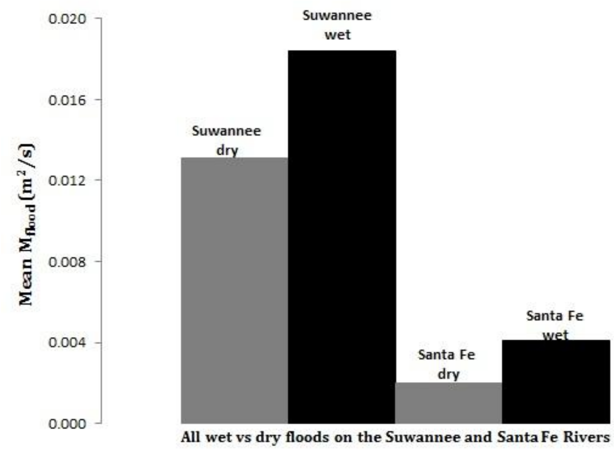

Figure 5. Quantification of average flood magnitude during wet and dry floods.

DISCUSSION

Dry and wet floods had distinctive differences. Dry floods were characterized by below average H_{GW} values, and had smaller flood magnitudes and higher P-ET values than the wet floods. As described below, it appears that H_{GW} is the controlling factor in flood magnitude and flood recharge.

Flood Recharge

The Suwannee and Santa Fe rivers had distinct wet and dry flood events during the period of study (Figure 6). During dry floods, the water table is lower than average; thus, more storage is available to accept recharge from the flood than during wet floods. For example, the flood in March 2008 on the Suwannee River had H_{GW} that were 14% lower than average (Figure 6), resulting in discharge 25% lower than average (Figure 3).

A cross plot of Q_{diff} to H_{GW} reflects the relationship between the groundwater levels and the magnitude of recharge to the Floridan Aquifer (Figure 7). Linear regressions model these relationships for the Suwannee River

$$Q_{diff} = -2.419\, H_{GW} + 2.8538 \quad \text{(eq. 6)}$$
$$R^2 = 0.8042$$

and Santa Fe River

$$Q_{diff} = -71.258\, H_{GW} + 84.487 \quad \text{(eq. 7)}$$
$$R^2 = 0.6553.$$

Even though recharge occurred to the Suwannee and Santa Fe rivers during all floods, the negative slopes in equations 6 and 7 indicate that higher recharge occurs to the Floridan Aquifer during dry floods than wet floods. The Suwannee River discharge was lower at Dowling by up to a factor of about 0.7 than at Ellaville gauging station during dry floods, while the Santa Fe River discharge was lower at Fort White gauging station by a factor of 15 than at Worthington gauging station over wet periods (Figure 7). Even during wet floods, the Suwannee River shows lower discharge at Dowling gauging station than at Ellaville gauging station by a factor of about 0.1. The Santa Fe River also shows lower discharge at Fort White gauging station than at Worthington gauging station by a factor of 7 during wet floods (Figure 7).

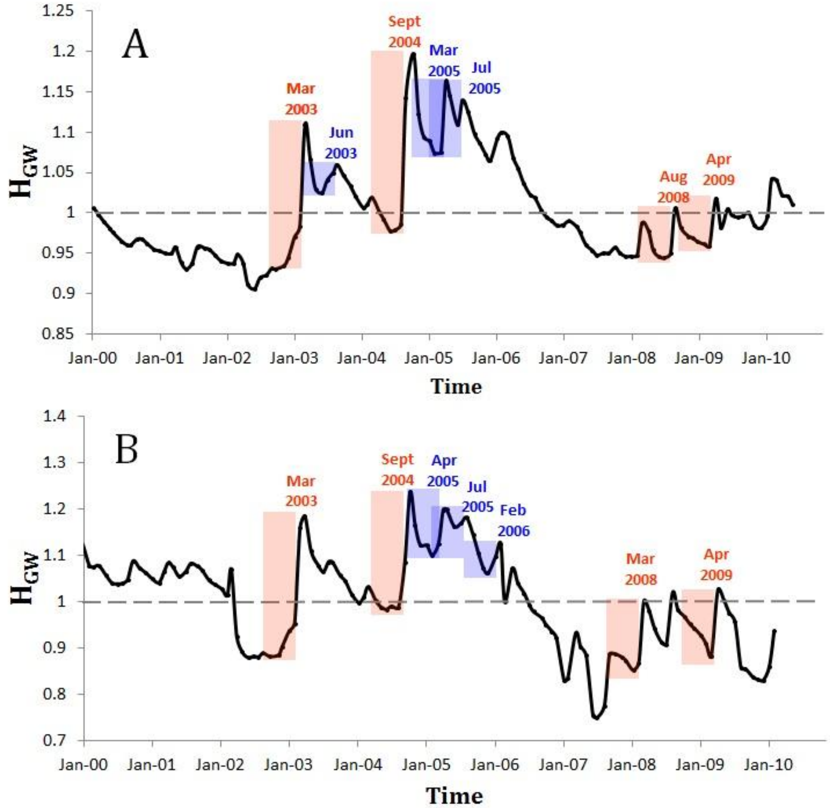

Figure 6. H_{GW} compared to time for A) Santa Fe River and B) Suwannee River.

Equations 6 and 7 indicate that Q_{diff} factor of recharge that will occur between two consecutive sites can be predicted based on the H_{GW} value. These equations could be used to predict both the magnitude of recharge to the Floridan Aquifer during floods as well as expected dampening of the flood through recharge to the aquifer. For example, when groundwater is at an average elevation (H_{GW} = 1), the Suwannee and Santa Fe rivers had differences between upstream and downstream discharges by a factor of 0.4 and 13, respectively (Figure 7). The difference in discharges between upstream and downstream could be the amount of water lost to the aquifer. Additionally, when Q_{diff} equals zero there is no change in discharge between upstream and downstream discharges. No difference in discharge between sites is found at 1.179 and 1.186 H_{GW} values. This indicates that groundwater elevations would have to be around 18% higher than average for both the Suwannee and Santa Fe rivers to prevent loss of discharge flood water between two consecutive sites.

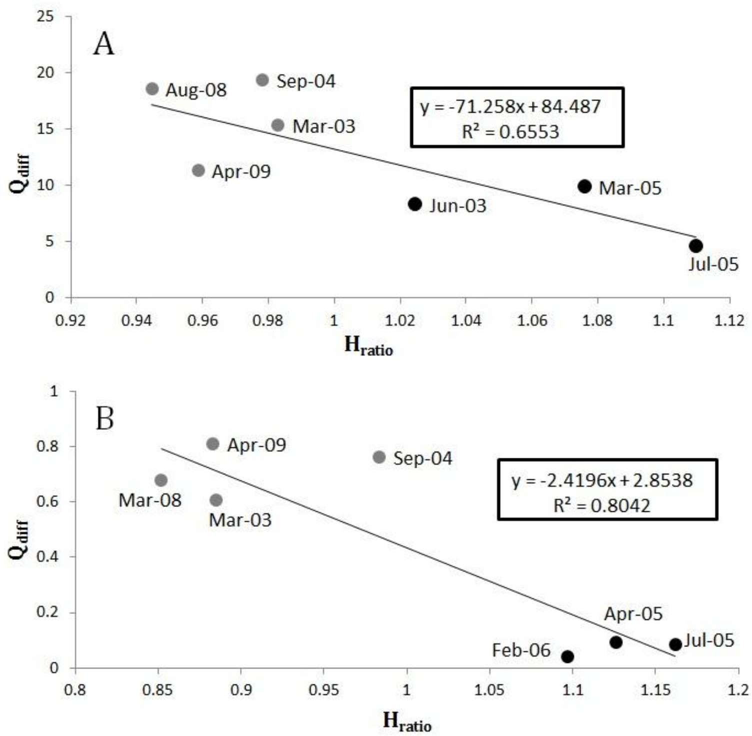

Figure 7. Cross plot of Q_{diff} vs H_{GW} for A) Worthington and Fort White on the Santa Fe River and B) Ellaville and Dowling gauging stations on the Suwannee River. Gray circles are dry floods, while black circles are wet floods.

Dry floods (low H_{Gw}) exhibited more recharge than wet floods (high H_{GW}) (Figure 8). In the Suwannee and Santa Fe rivers, between sites Ellaville/Dowling and Worthington/Fort White, dry floods were found to have two and five times more recharge than wet floods, respectively. Recharge between sites is assumed when upstream discharges are larger than downstream. Dry floods may have more recharge because of lower antecedent H_{GW} levels. Lower H_{GW} levels mean that there is more room in the vadose zone for flood water recharge. Conversely, wet floods have less recharge because of higher antecedent H_{GW} levels. Higher H_{GW} levels mean that there is less room in the vadose zone for flood recharge.

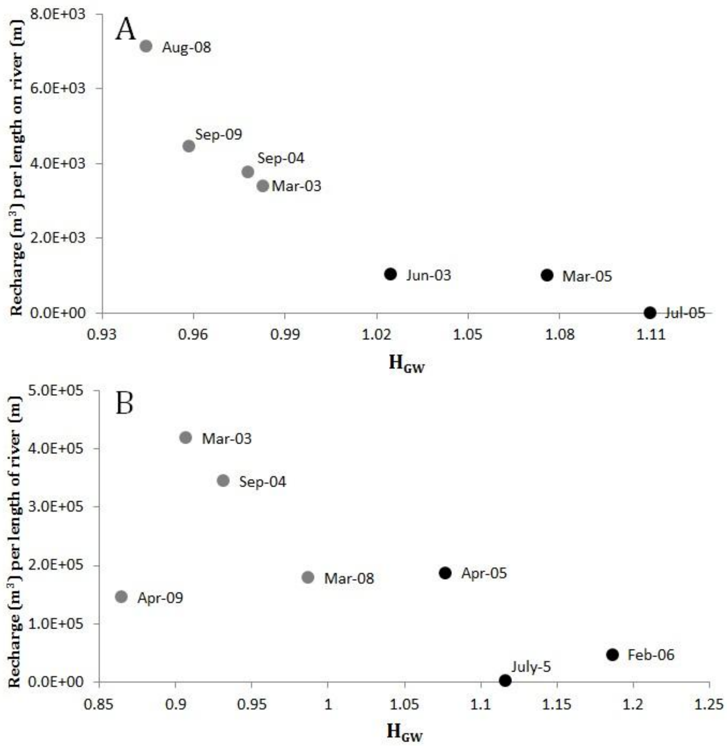

Figure 8. Amount of recharge during flood event between A) Worthington and Fort White on the Santa Fe River and B) Ellaville and Dowling gauging stations on the Suwannee River.

Flood Magnitudes

Generally, M_{flood} values are smaller for dry floods than wet floods (Figure 5). M_{flood} values depend on H_{GW} conditions and not P-ET conditions. Floods were produced during both large P-ET events and during small P-ET events (Figure 2). Small P-ET events caused floods during periods of high H_{GW} (i.e., wet floods) and were mostly larger magnitude floods (Figures 3, 5, 6). Conversely, large P-ET events caused floods during periods of low H_{GW} (i.e., dry floods) and were mostly smaller magnitude floods (Figures 3, 5, 6). During dry floods, river magnitudes are minimized due to flood water recharge into the aquifer. However, during wet floods, the aquifer H_{GW} values are higher and allow less flood water recharge into the aquifer, thus causing larger magnitude floods (i.e., larger M_{flood} values).

The amount of rain required to cause floods appears to be also influenced by which basin the flood occurs in. Smaller M_{flood} values were found in the Santa Fe River basin than in the Suwannee River basin (Figure 5). This difference may occur because the Santa Fe River needs less rain to create a flood because the surrounding basin is a large allogenic catchment. Most of the Santa Fe extends above the Cody Scarp (where water is able to quickly drain into the Santa Fe River) (Figure 1). Also, the Suwannee River extends into Southern Georgia, but the P-ET data used in this project were purely Florida data. To better improve this data, P-ET data from southern Georgia should be used to better understand the northern part of the Suwannee River's M_{flood} value.

CONCLUSIONS

This project provides information about the relationship between flooding, groundwater levels, and recharge of the Floridan Aquifer and shows that the amount of groundwater recharge depends on the relative hydraulic heads in the groundwater and surface water.

Wet floods were defined here to occur when groundwater elevation was higher than average, while dry floods were defined to occur when groundwater elevation was lower than the average over the 10-year period of record. Wet floods were found to have less recharge of flood water to the Floridan Aquifer System than dry floods. Recharge during wet floods was minimized because storage capacity of the aquifer was already filled, while recharge during dry floods was enhanced because of larger storage capacity. The amount of recharge has important implications for potential contamination of the aquifer.

Information about antecedent surface water conditions and storativity in the Floridan Aquifer System should improve model prediction of flood magnitude and the potential for contamination associated with the floods.

These techniques may be applicable to any river/aquifer system but would be particularly important for karst systems.

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