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IMPACT OF ANTECEDENT GROUNDWATER HEADS AND TRANSIENT AQUIFER STORAGE ON FLOOD PEAK ATTENUATION IN AN UNCONFINED KARST AQUIFER: STUDY OF THE UPPER SUWANNEE RIVER, FLORIDA, USA.

Jeremy Loucks
Michigan Technological University, jmloucks@mtu.edu

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Jeremy M. Loucks

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Department of Geological and Mining Engineering and Sciences

Thesis Advisor: *Dr. Jason Gulley*

Committee Member: *Dr. John Gierke*

Committee Member: *Dr. Alexandria Guth*

Department Chair: *Dr. John Gierke*

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Abstract

Flood peak attenuation is an important aspect of understanding flooding and its effects. Few studies exist that look at the effects of ground-surface water interactions in regards to peak attenuation, and fewer still focus on karst environments. In the karstic, variably confined Suwannee River Basin, discharge, river stage, and water table data that were collected over a ten-year period were analyzed to determine the relationship between antecedent groundwater head and flood peak attenuation. Flooding causes high hydraulic heads in the river, which rise faster than corresponding groundwater heads. Springs which normally feed groundwater into the river reverse flow, and conduits allow for large amounts of river water to be absorbed into the aquifer matrix. Peak discharge in floods that occurred when antecedent groundwater heads were low were attenuated downstream. In contrast, peak discharge in floods that occurred when antecedent groundwater heads were high lacked attenuation Because most flood discharge models do not consider how transient storage of floodwaters in aquifers can attenuate flood peaks, predictions and flood warnings may be inaccurate in basins that promote peak attenuation, such as unconfined karstic basins. In addition, understanding these interactions is paramount in determining pollution risks to karst aquifer systems.

Introduction

Floods kill more people in the United States than any other weather phenomenon (Mogil et al 1978) and cause $2.67 billion of damage annually (Changnon 2008). Improved flood prediction capabilities are needed as population and infrastructure investment increase in flood prone regions.

Commonly used flood prediction models are generally successful at predicting peak flood discharges in river basins where peak flood discharge increases downstream. Discharge increases downstream because an increasingly large number of tributaries contribute flow to the main stem of the river. Because discharge at downstream locations is a function of rainfall amount and runoff from upstream locations, flood peaks at downstream locations can be predicted using a combination of historical flow data during floods, advanced precipitation modeling, basin characteristics, stage heights, runoff, and discharge (Knebl et al 2005).

Flood prediction models are less successful at predicting peak flood discharges in basins where flood peaks decrease with distance downstream (flood peak attenuation). Basins with attenuation can break the direct relationship between rainfall, runoff, and downstream discharge because some flood waters can be diverted to temporary storage, often as bank or aquifer storage. Temporary storage of flood waters attenuates the peak discharge and spreads it out over time, lessening the flood's impact downstream (Chen and Chen 2003, Chen et al 2006). While flood models take into account many variables, storage such as this is not considered and can have a significant impact on flood events (Zanon et al 2010).

Storage and flood peak attenuation is well understood when storage occurs in surface storage elements. Lowland rivers have been found to attenuate floods when rivers overtop their banks, allowing large volumes of water to be stored in floodplains (Woltemade and Potter 1994, Stewart et al 1999, Burt et al 2002). This excess water flows back into the river after the flood peak passes.

Storage and flood peak attenuation is less well understood when storage of flood waters occurs in aquifers. In river basins where water flows from catchments underlain by low-permeability rocks, such as mountain slopes, onto catchments underlain by higher permeability rocks, such as alluvial valleys, runoff from impermeable rocks can rapidly increase river stage downstream (Montaldo et al 2004). If runoff increases river stage faster than infiltration of rainfall can increase groundwater heads, then normal hydraulic gradients between the river and aquifer can be reversed, causing flood waters to flow from the river into the aquifer (Lauber et al 2014). Under these circumstances, flood waters can flow from the channel and be stored with in the vadose zone of river banks (bank storage), attenuating peak flood discharge at downstream locations. Antecedent groundwater heads are an important control on aquifer storage capacity, as the elevation of the water table relative to river stage controls the direction and magnitude of water exchange between the river and aquifer. Additionally, magnitudes of storage are limited by the permeability of the vadose zone substrate, which controls exchange rates of river water, and effective porosity, which controls the storage capacity (Chen and Chen 2003, Chen et al 2006).

Transient aquifer storage of floodwaters, and hence flood peak attenuation, should be particularly enhanced where rivers flow over karst aquifers. Conduits and cave systems in karst aquifers increase connectivity between rivers and aquifers (Alberic

2004, Gulley et al 2013) and can store large volumes of water where they are air-filled (Baffaut and Benson 2009). Consequently, the capacity for flood peak attenuation should be high relative to rivers that do not flow over karst aquifers, however, little work has investigated the role of transient aquifer storage on flood peak attenuation in karst aquifers.

Most work on transient aquifer storage in karstic watersheds has emphasized understanding surface and groundwater exchange in sink-rise systems, where water enters an upstream conduit and discharges downstream via springs (Martin and Dean 2001, Bailly-Comte et al 2011, Gulley et al 2011). In these systems, flood peaks are attenuated as floodwaters are temporarily forced out of conduits and into the aquifer, attenuation peak discharge and diffusing discharge over longer time periods at the spring. Consequently, flood peaks at downstream springs are attenuated due to transient aquifer storage.

While springs are typically conceptualized as unidirectional discharge points of karst aquifers, many karst springs reverse flow during floods (Katz et al 1997, Crandall et al 1999, Alberic 2004). For example, in karst catchments that receive runoff from adjacent catchments that are underlain by low permeability rocks, runoff can increase river stage faster than local infiltration of rainfall can increase groundwater heads, causing springs to reverse to flow (Grubbs 1998). Because reversing springs are connected to extensive cave systems, conduits allow flood waters to penetrate deep into aquifers where flood waters can exchange with, and be stored in, the matrix (Grubbs 1998, Crandall et al 1999, Alberic 2004, Gulley et al 2011). Air-filled and water-filled caves differ in their storage location once the water reaches deep into the aquifer. In air-filled caves, storage can be in conduit, as well as matrix, porosity. In water-filled cave systems, storage occurs when floodwater flows from conduits into the matrix, locally elevating the water table; storage thus occurs in the vadose matrix porosity (Martin and Screaton 2001, Bailly-Comte et al 2011). Consequently, whether they are air or water filled, conduits that are characteristic of karst aquifers should thus allow for greater exchange of floodwaters and aquifers, and hence flood peak attenuation, than in rivers that flow over rocks with similar hydraulic properties, but lack conduits.

In this study we investigate the impact of surface-groundwater interactions and transient aquifer storage of floodwaters on flood peak attenuation in a reach of the karstic Upper Suwannee River basin, in north-central Florida. Understanding surface water-groundwater interactions are critical in creating accurate flooding models for the region, as current ones do not take into account their exchange. We also quantify the role of antecedent groundwater heads on flood peak attenuation by determining if there was a correlation between the two. This was done by analyzing the relationship of antecedent groundwater heads to flooding events and discharge volumes in this basin. In addition, a better understanding of the processes that lead to spring reversals, aquifer storage and bank storage allow for a greater understanding of pollution risks involved in rapid aquifer infiltration.

Geologic Setting

The Suwannee River basin drains 25,830 km^2 and discharges water to the Gulf of Mexico (Planert 2007). This study emphasizes an 84 km stretch of the Suwannee River-between the Ellaville and Branford gaging stations operated by the United States

Geological Survey (USGS 2319500 and USGS 2320500, respectively) (Figure 1). The total catchment area for the Branford gaging station is approximately 20,400 km^2. This reach of the Suwannee River is underlain by three major lithological units that make up a large portion of the Upper Floridian Aquifer: The Hawthorn Formation, which consists mostly of clays, sands and other siliciclastics, the Suwannee Limestone, and the Ocala Limestone. The Hawthorn Formation overlies the Suwannee and Ocala limestones and frequently acts as a confining unit when present. Erosion has removed the Hawthorn Formation in the southern portion of the basin, leaving the highly porous Ocala Limestone exposed at the surface. Where erosion has removed the protective layer of siliciclastics, limestone has been highly karstified. Both the Suwannee and Ocala limestones are heavily eroded and have high porosity, permeability, and aquifer transmissivity (Scott 1992). Due to these conditions, the Ocala and Suwannee limestones are able to store and move large quantities of water through conduits and aquifer matrices.

Figure 1

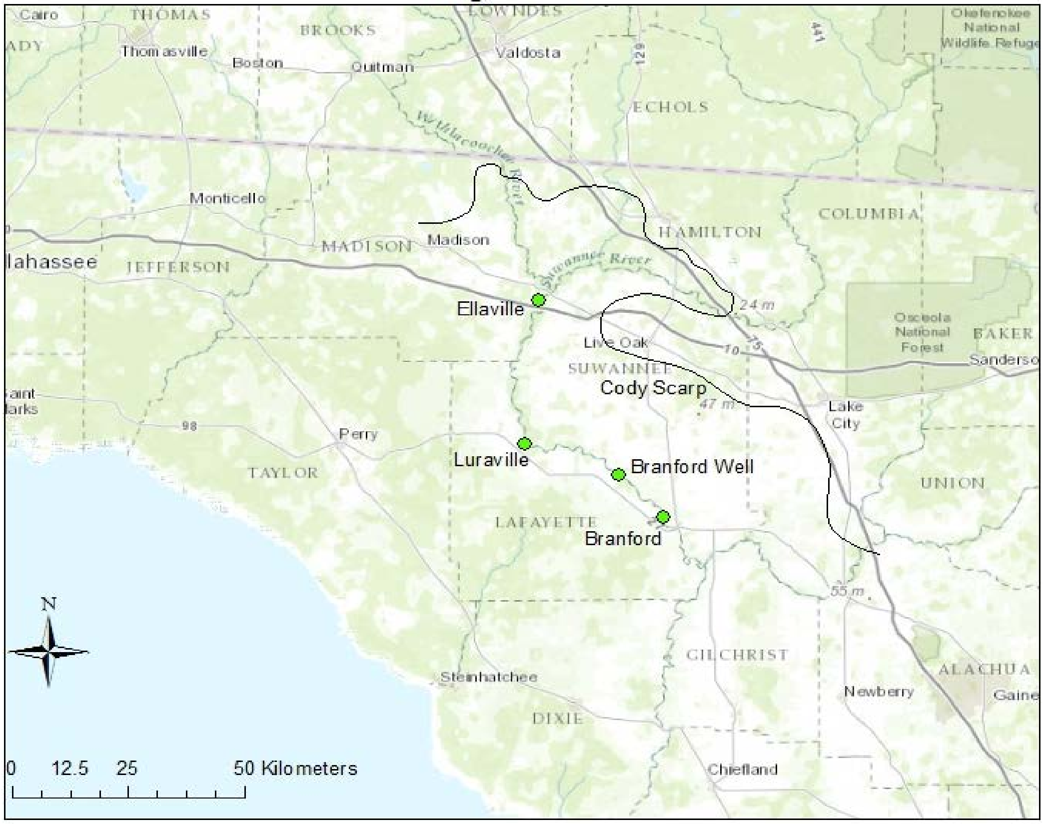


Figure 1: Map of the Lower Suwannee River, with stream gage and well locations, and a rough outline of the Cody Scarp. Modified from www.ArcGis.com.

As the Suwannee River flows from its northern reaches, it crosses the Cody Scarp, the geologic boundary of the confined portion of the upper Floridian aquifer. The Cody Scarp also serves as the boundary between the Upper and Lower Suwannee River Basins. The formations upstream of this dividing line have low permeabilities and protective Hawthorn Formation surficial clay deposits, facilitating flooding. Downstream from the Cody Scarp, the Ocala and Suwannee Limestones are unconfined and their high permeability allows for rapid infiltration of rainfall. High permeability limits surface water ponding, and, consequently, surface water only exists where the water table intersects low points in the surface topography, such as karst windows or the eroded river channels (Gulley et al. 2014). As a result, only two rivers exist on top of the unconfined aquifer, the Suwannee River and its tributary, the Santa Fe River.

During base flow, the lower Suwannee River is a gaining stream, with discharge increasing due to groundwater inflow from the upper Florida aquifer. Most of this inflow comes from conduit-fed springs, with lesser contributions from non-conduit matrix permeability (Pittman et al 1997). For example, between the Dowling Park and Branford gaging stations, base flow discharge increases by 50%, with 40% of the increase coming from monitored springs alone (Pittman et al 1997, Katz et al 1997).

Flooding in the lower Suwannee River occurs when storm runoff from the upper basin crosses the Cody Scarp. During flooding, the rapid increase in river stage causes a reversal in normal head gradients between the river and aquifer, leading to spring reversals. Spring reversals and transient storage of floodwaters in the aquifer have been confirmed by geochemical studies in wells (Crandall et al 1999, Katz et al 1997), studies in conduits and direct measurement of spring discharge magnitude and direction (Gulley et al 2013, Gulley et al 2014). These spring reversals cause the Suwannee River to transition from a gaining stream during baseflow to a losing stream during floods. The transition from gaining to losing stream indicates flood peaks are being attenuated as a result of transient aquifer storage. Intuitively, floods that occur immediately after dry periods should experience more attenuation than a similar magnitude flood occurring after a wet period. Greater attenuation should result because lower water tables following dry periods should increase storage capacity for flood waters and result in steeper hydraulic gradients between the river and the aquifer during flooding. We are not, however, aware of any studies that have investigated the role of antecedent groundwater heads in controlling magnitudes of flood peak attenuation in karstic watersheds.

Methods

We used average daily river discharge and stage data from select gaging stations in the Suwannee River basin to relate magnitudes of flood peak attenuation to antecedent groundwater heads. Data was analyzed from between January 1, 2003 and December 31, 2013. This period was selected on the basis of well data availability and because the USGS had not approved discharge data newer than December 31, 2013 at the time this study began.

We downloaded daily average discharge and stage data from the USGS water watch database (www.waterwatch.usgs.gov) from the Ellaville (USGS 02319500), Luraville (USGS 02320000), and Branford (USGS 02320500) gaging stations. All three gages use the 1929 NGVD datum, with Ellaville and Branford's gages located 8.3m and 1.5m above it, respectively. The Ellaville and Branford gage data were then corrected to the 1929 NGVD datum. Data were collected every fifteen minutes and reported as daily averages.

We obtained water table elevation data from wells from the Suwannee River Water Management District website (www.mysuwanneeriver.org/portal/groundwater.htm). We obtained water table elevations from a well (S015334013) located 9.6 km upstream of the Branford discharge gage and 0.16 km. Water table elevations in wells were measured at coarser intervals than river data. From 2003 to 2011 dates, water table elevations were measured roughly once a month, varying from a few days to nearly two months, while from 2012 to 2013 they were measured only six total times. There was only one well measurement for all of early 2013, during February.

Well data were used to determine if the elevation of the water table was above or below the average elevation prior to a flood event. For the purposes of this study, we define a flood as events where the instantaneous discharge at each gaging station attained a minimum of 300 m^3/s, which is approximately three times the base level flow. For brevity, we refer to these events hereafter as “floods,” although the events might not have overtopped the stream banks. Twenty floods occurred during the study period. Flood events were cross-referenced against the well data to determine which events had both river discharge and water table elevation data within two months prior to the event. Based on these criteria, we identified eleven events.

We assessed groundwater heads immediately prior to a flood using two complementary measurements, water table elevations in wells and river. The well data is clearly a direct indication of groundwater heads, but as discussed above, coarse sampling intervals limited data availability. Consequently, we also used river stage, which is recorded continuously, as an indicator of antecedent groundwater heads. During base flow conditions, the Suwannee River is the lowest head in the aquifer (Crane 1986), meaning river stage prior to floods can be used as an indicator of groundwater heads in the Suwannee River Basin.

We plotted the ratio of discharge from Ellaville to Branford against antecedent well elevations and river stages to determine if any relationships existed. Ellaville was chosen as the upstream measuring station because all discharge from the upper basin flows through it after passing over the Cody Scarp. Branford is the final gaging station at the end of an 84km stretch between Ellaville and the nearest tributary, the Santa Fe River, enters the Suwannee.

Relating the ratio of discharge at Branford and Ellaville to the antecedent groundwater head allows us to determine if the magnitude of flood peak attenuation is related to water table elevation prior to flood events. A discharge ratio of one means that the stream neither gains nor loses water between gaging stations. A ratio above one means that the river gains water as the flood peak moves downstream. A ratio below one means that the surge attenuates downstream and the river loses water. If this relationship between discharge ratio and antecedent groundwater heads varies systematically, then antecedent groundwater heads may control flood peak attenuation.

Understanding the record of accuracy for National Weather Service (NWS) flood warnings allows us to determine if integrating transient aquifer storage could allow for greater accuracy in future forecasts. We cross-referenced the flood events as determined by our study with a database of NWS past issued warnings, using the Iowa State University website (mesonet.agron.iastate.edu/wx/afos/). Five floods were sufficiently large to warrant warnings being issued. For those floods, we gathered stage height predictions between one and seven days in advance of the peak discharge.

Results

Flood Analysis

River discharge downriver at Branford varied from a low of 35 m^3/s in May 2012 to a high of 1,184 m^3/s in April 2009. Between 2003 and 2013, there were eleven flood events that had discharges of over 300 m^3/s at all gaging stations while also having matching antecedent well data during the study period (Fig. 2) Ranking by discharge upstream, at Ellaville, the floods were, from smallest to largest: August 2003 (331 m^3/s), February 2006 (348 m^3/s), February 2004 (388 m^3/s), June 2005 (402 m^3/s), February 2010 (521 m^3/s), March 2008 (572 m^3/s), March 2013 (810 m^3/s), March 2003 (872 m^3/s), October 2004 (932 m^3/s), April 2005 (1,133 m^3/s), and April 2009 (1,597 m^3/s).

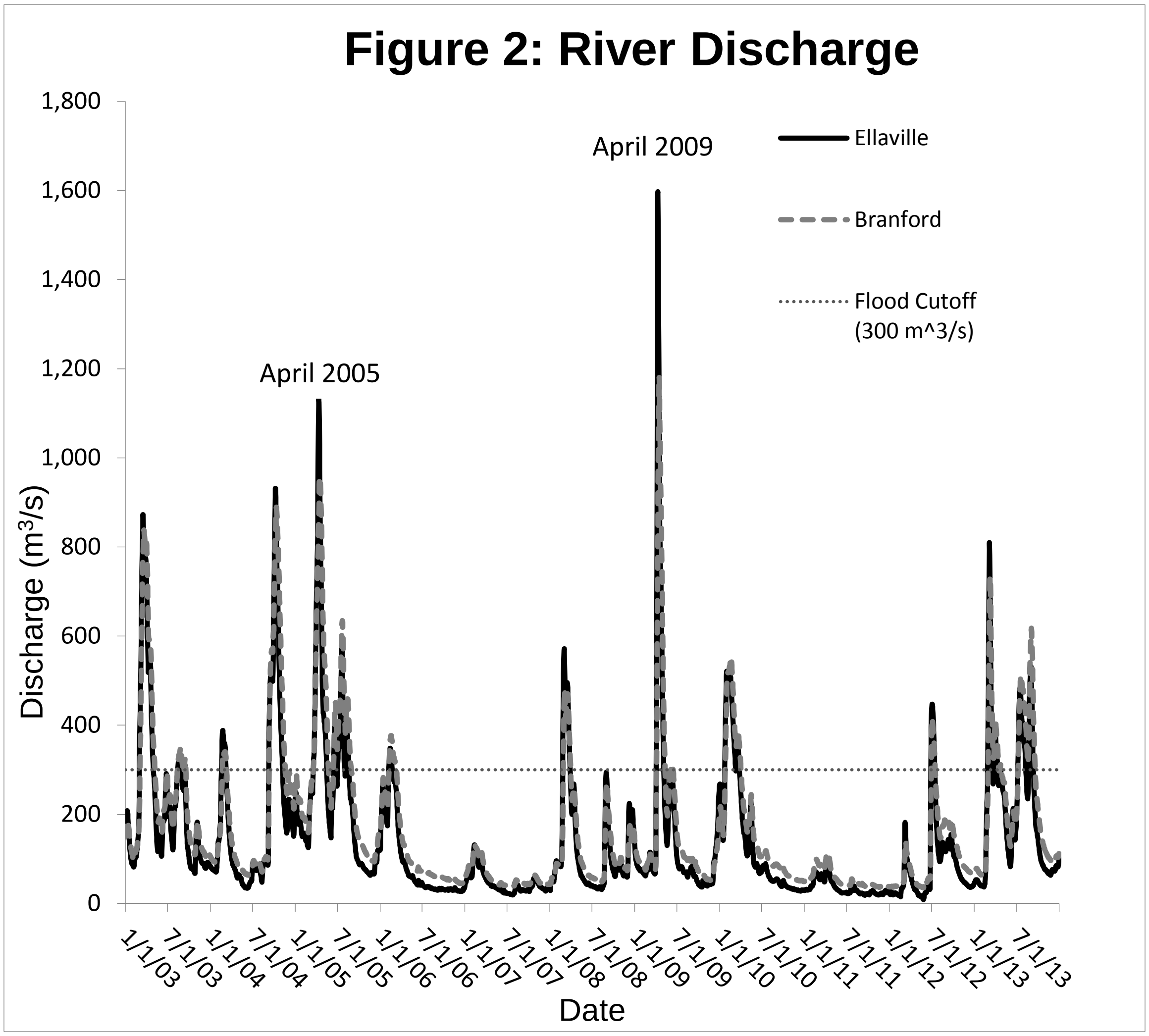
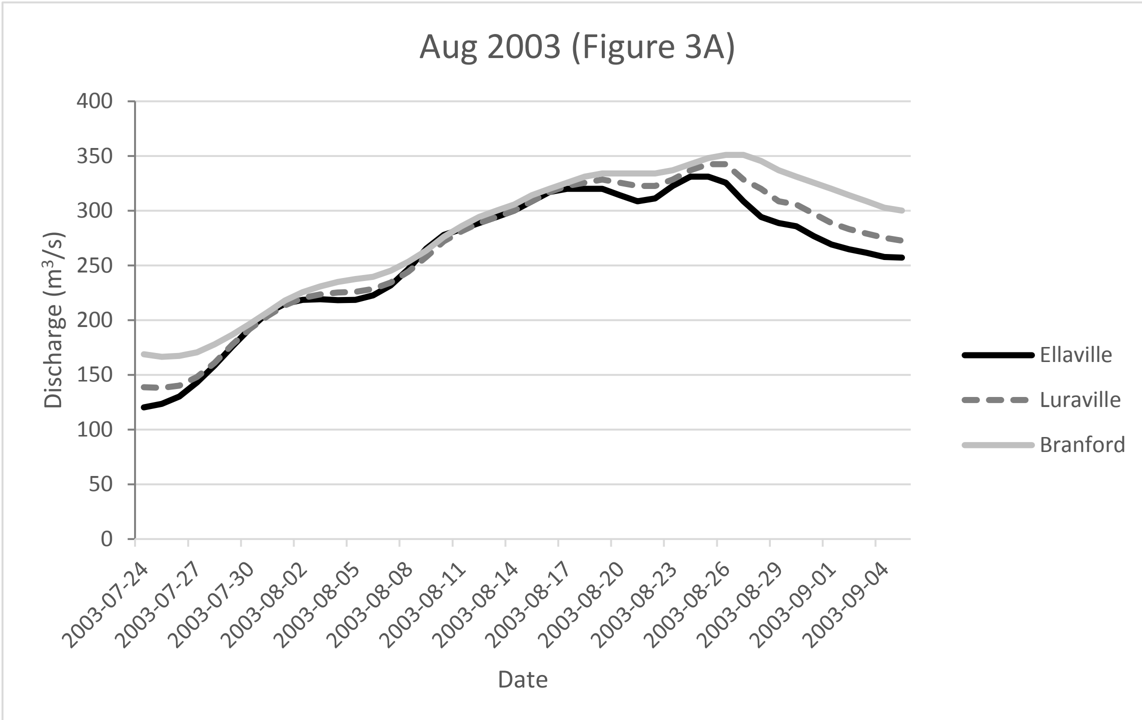


Figure 2: Discharge data, in m^3/s from Ellaville, Luraville, and Branford gaging stations over the study time period. The dashed line at 300 m^3/s represents the discharge cutoff

line for identifying flood events. Note the extreme floods of April 2005 and April 2009, as well as the significant drought periods of mid 2006 - early 2008 and mid 2010 – late 2012.

Of the eleven flood events with both stage and well data that were used in the study, eight of them showed attenuation as flood peaks moved downstream (Fig 2). Of these eight, six had well heights below average, and five had stage heights below average. Floods that showed attenuation had discharges that spanned a wide range (387-1,597 m^3/s) at Ellaville. In contrast, the three floods that showed no attenuation all had above average well and stage heights. Non-attenuating floods had a more uniform distribution, varying only from 331-402 m^3/s at Ellaville. Floods where peak discharge increases downstream were associated with lower magnitude events whereas peak discharge decreased downstream for larger magnitude events (Fig 3). For example, the August 2003 flood, peak discharge at Ellaville was 331 m^3/s and discharge increased by 20 m^3/s downstream (Figure 3A). In contrast, in the March 2013 flood (Figure 3B), discharge at Ellaville was 810 m^3/s and it decreased by 77 m^3/s downstream.


Aug 2003 (Figure 3A)
Discharge (m³/s)
400
350
300
250
200
150
100
50
0
2003-07-24
2003-07-27
2003-07-30
2003-08-02
2003-08-05
2003-08-08
2003-08-11
2003-08-14
2003-08-17
2003-08-20
2003-08-23
2003-08-26
2003-08-29
2003-09-01
2003-09-04
Date
Ellaville
Luraville
Branford

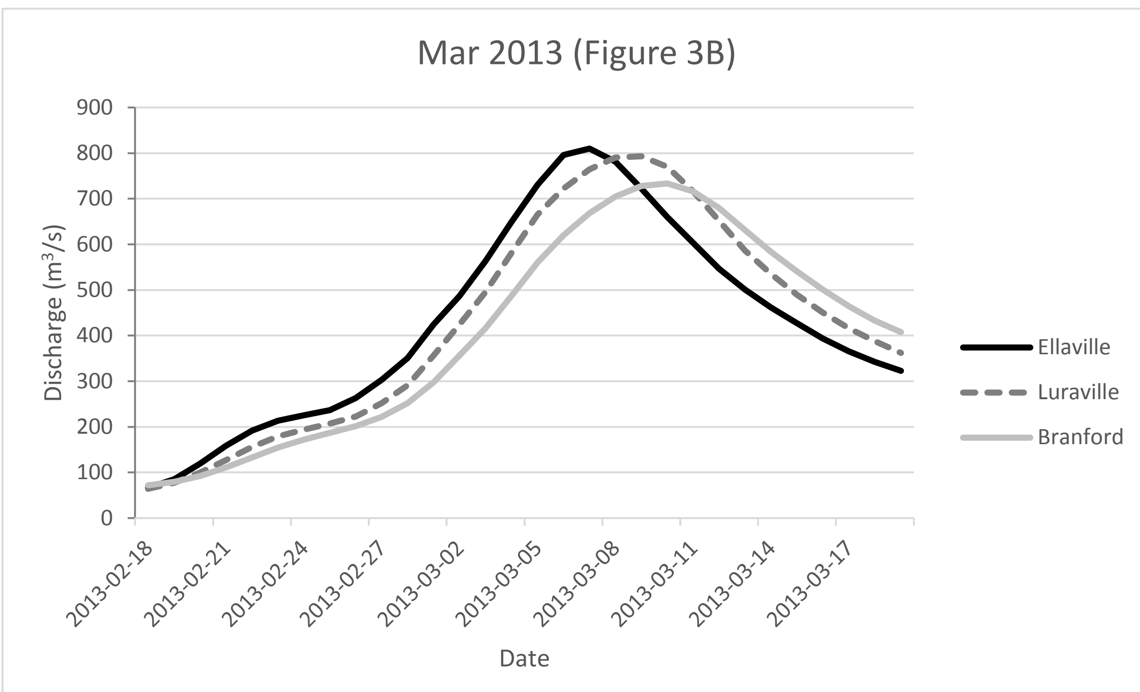

Mar 2013 (Figure 3B)
Discharge (m³/s)
900
800
700
600
500
400
300
200
100
0
2013-02-18
2013-02-21
2013-02-24
2013-02-27
2013-03-02
2013-03-05
2013-03-08
2013-03-11
2013-03-14
2013-03-17
Date
Ellaville
Luraville
Branford

Figure 3: Hydrographs of flood events on the Suwanee River. **A)** During the August 2003 flood, discharge increases downstream from Ellaville to Branford, where Branford exhibits peak flow. **B)** During the March 2013 flood where discharge decreases downstream from Ellaville to Bradford and exhibits significant attenuation from peak flow.

Well and Stage Data

Water table elevations measured in wells fluctuated with river stage (Fig 4). The average measured water table elevation during the period of study was 4.68 meters (NGVD 1929 Datum), but was higher during floods and lower during droughts. The highest water table elevation was 9.48 m (April 2005) and the lowest was 3.02 m (January 2012). River stage at Branford for those measurements was 8.90 m and 2.05 m, respectively. Lengthy droughts in 2006-2008 and mid 2010-2012 in particular resulted in low water table elevations.

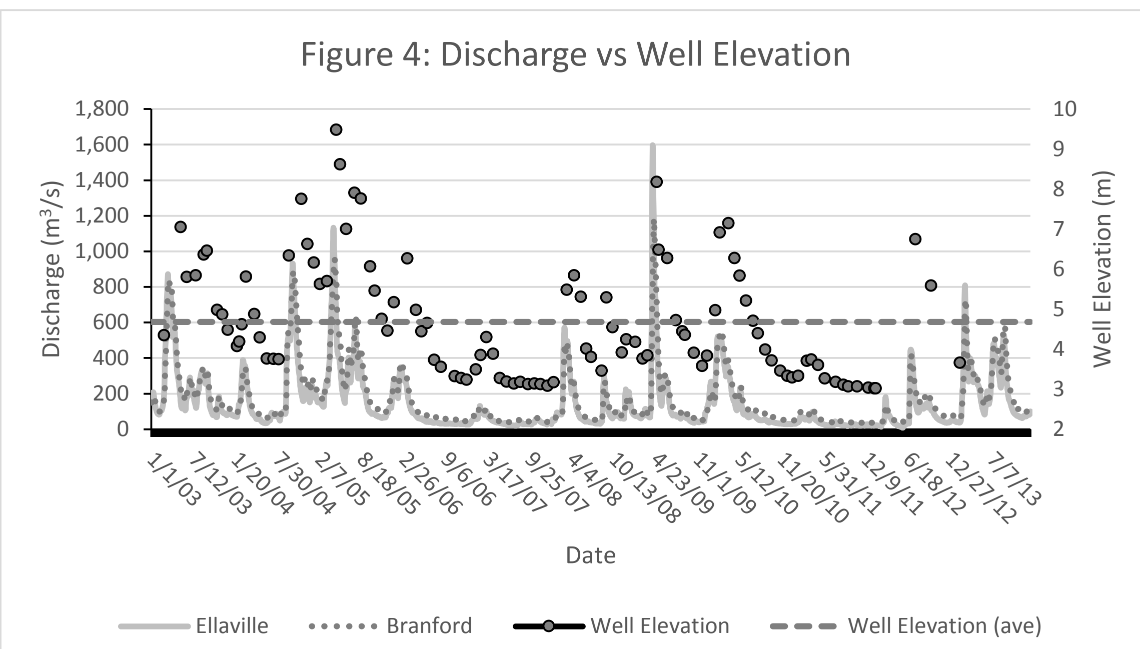


Figure 4: Comparing discharge from Ellaville and Branford gaging stations to measured well heights at Branford well. The well height average over the study period is the dashed line across the graph and reflects periods of wet vs dry conditions.

Water table elevation just prior to flood events ranged from a low of 3.17m (March 2008) to a high of 7m (June 2005), but no measurements of water table elevation were available from February to mid-September in 2013.

Flood peak attenuation and antecedent water table elevation in wells

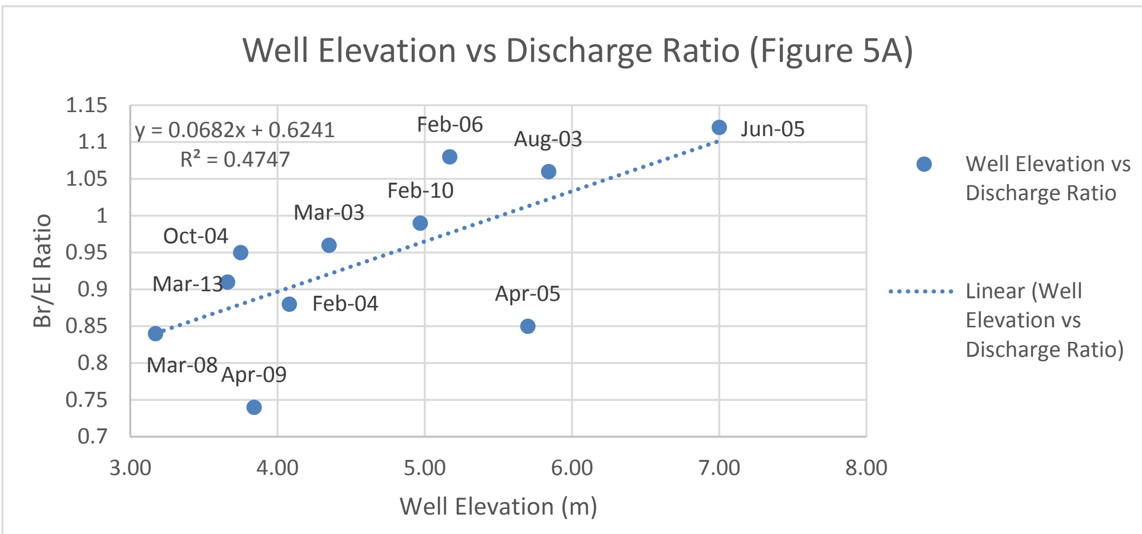
The greatest flood peak attenuation almost always occurred in floods where antecedent groundwater heads were below average (Table 1). The water table elevations of the six attenuated floods, removing April 2005 and April 2009, ranged from 7-32% below average, while discharge downstream decreased from 1-16%.

Table 1: Listing of each flood with antecedent well elevations, discharge ratios, and antecedent stage heights, sorted by discharge ratio. The four shaded floods (Apr-05, Mar-08, Apr-09, and Feb-10) were considered discrepant, which is explored in the discussion.

Table 1. Discharge Ratios and Water Elevations				
Peak Discharge Ratio	Well Elevation (m)	Well Date	Peak Date	Antecedent Stage Height (m)
Branford/Ellaville	Branford	Branford		Branford
0.74	3.84	3/17/09	Apr-09	2.85
0.84	3.17	1/14/08	Mar-08	2.97
0.85	5.70	3/14/05	Apr-05	4.07
0.88	4.08	1/27/04	Feb-04	3.09
0.91	3.66	2/12/13	Mar-13	2.78
0.93			Jul-12	2.45
0.95	3.75	8/4/04	Oct-04	3.33
0.95			Mar-08	6.39
0.96	4.35	2/28/03	Mar-03	4.04
0.99	4.97	1/22/10	Feb-10	4.22
1.03			Apr-13	5.68
1.06	5.84	7/22/03	Aug-03	4.24
1.06			Jul-13	4.29
1.08	5.17	1/13/06	Feb-06	4.83
1.08			Feb-10	7.20
1.10			Jul-05	6.09
1.10			Mar-10	6.10
1.12	7.00	6/10/05	Jun-05	4.97
1.16			Sep-13	5.60
1.21			Aug-05	6.33

Less flood peak attenuation (or flood peak augmentation) occurred when antecedent groundwater heads were above average. The water table elevations of the three non-attenuated events ranged from 10-50% above average while discharge increased downstream between 6-12%.

Ratios of peak discharge at upstream and downstream gaging stations for each flood event are linearly and positively correlated with antecedent groundwater head (R^2 = 0.47) (Fig 5). The magnitude of flood peak attenuation increases as antecedent groundwater head decreases (Fig 5). The April 2005 and April 2009 flood events had peak discharge values that were much higher than the other floods (1,133 m^3/s and 1,597 m^3/s, respectively). Removing these events from our analysis improved the goodness of fit (R^2 = 0.85).



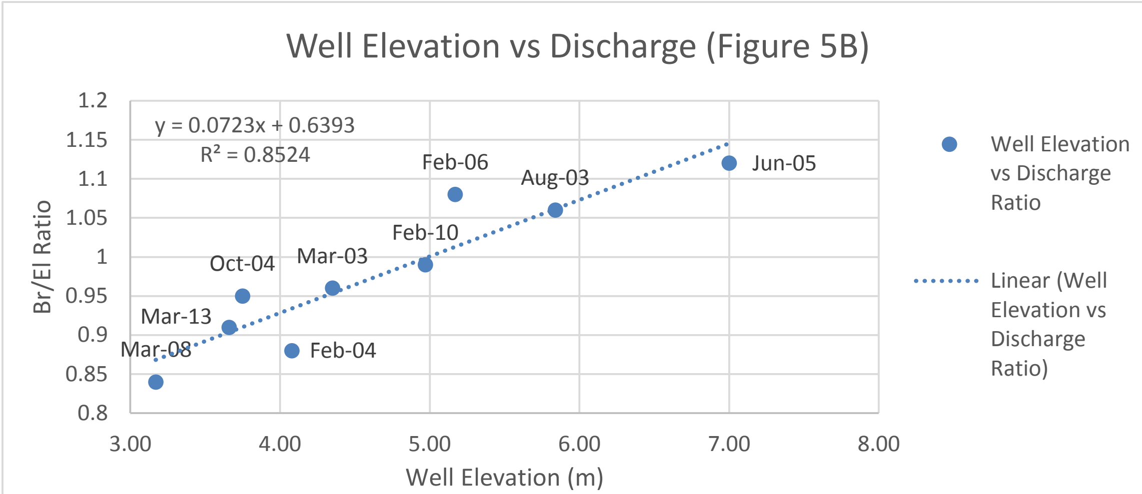
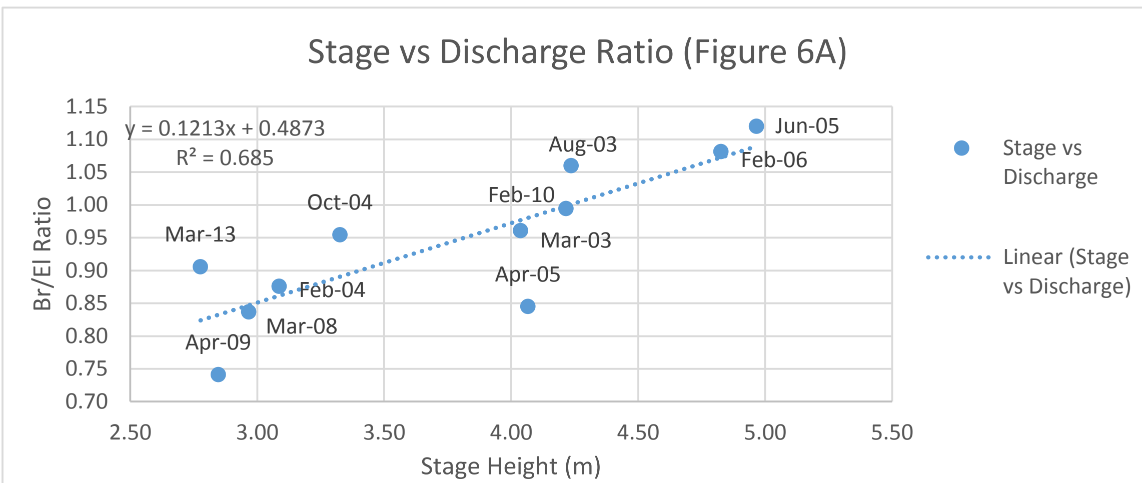
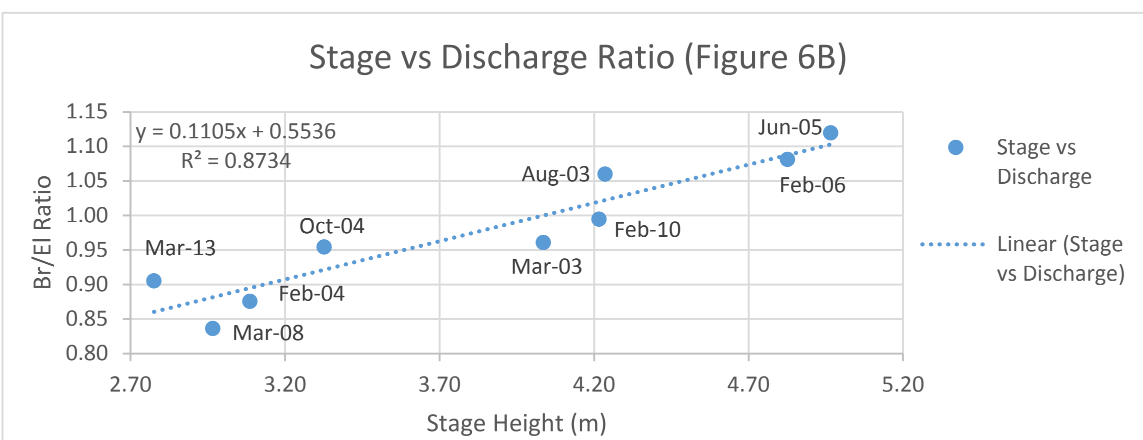


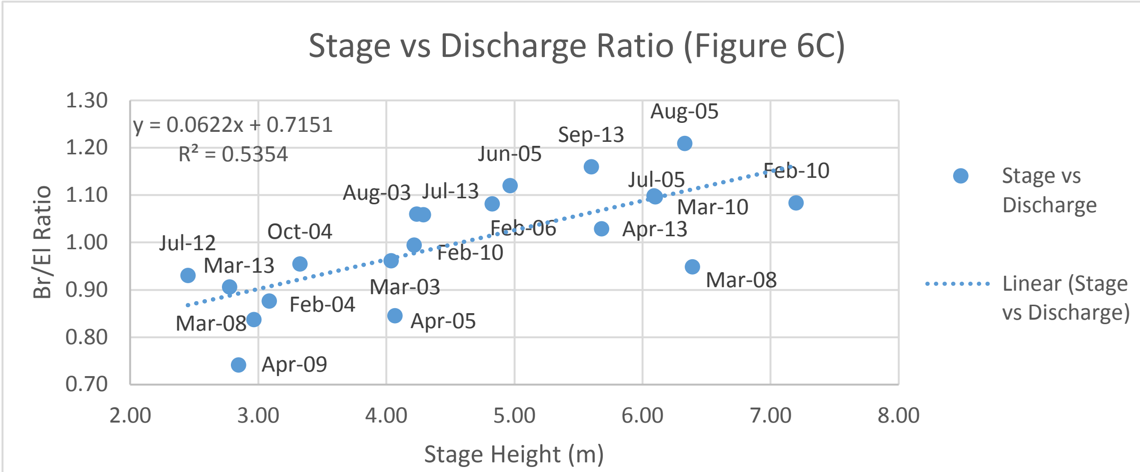
Figure 5: Well Elevations vs Discharge Ratios for the selected flood events. A) All eleven flood events along with a best fit line. B) The nine flood events after the April 2005 and April 2009 floods had been removed, with a much better fitting regression line.

Relationships between antecedent groundwater heads determined using river stage are similar to those determined from well data. Of the three floods that showed no attenuation, all of them had above-average antecedent stage height (11-41% above). In contrast, 5 of 8 attenuating floods had below average stage heights (25-44% below) and the other three attenuating floods antecedent stage heights only slightly above average, ranging from 4-11% above.

Ratios of peak discharge at upstream and downstream gaging stations for each flood event are also linearly and positively correlated with antecedent river stage (R^2 = 0.68) (Fig 6A). Again, goodness of fit was improved by removing the April 2005 and April 2009 flood events (R^2=0.87) (Fig 6B). Because antecedent river stage data was available for all twenty floods identified by the study, whereas groundwater head data from wells was only available for eleven floods, we conducted a separate analysis using all twenty floods. There was again a linear, positive correlation, but the goodness of fit decreased (R^2 = 0.54) relative to Figure 6A (Fig 6C). The April 2005 and April 2009 floods were removed as in Figure 6B, and the secondary March 2008 and secondary February 2010 floods were removed due to a flood recurrence interval of only twelve days between a prior flood peak and the peak of the removed event, which will be explained in the discussion. Doing so improved the goodness of fit (R^2 = 0.77) (Fig 6D).







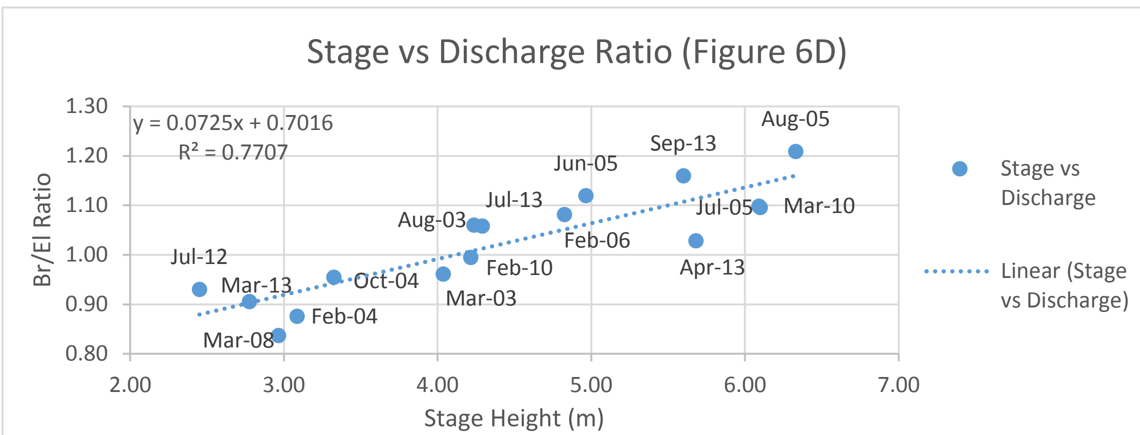


Figure 6: River stage vs Discharge ratios. A) Plot of all eleven featured flood events. B) Plot of the nine flood events, having removed the April 2005 and April 2009 floods. Note how much more linear the data are, showing a very strong positive linear relationship. C) Plot of all twenty flood events from the study period. D) Plot of all flood events with April 2005, April 2009, March 2008, and February 2010 removed.

By cross-referencing a database of historical NWS flood warnings with the flood peaks we identified in the study, we found five with issued warnings for Branford: March

2003, October 2004, April 2005, April 2009, and March 2013. All of these events reached flood stage. For the period from 2003-2009, the NWS released warnings with predicted stages for the next five days. Of those warnings, the March 2003, October 2004, and April 2005 warnings were all closely accurate, with predicted stage heights ranging from 0.11m lower to 0.26m higher than measured. The April 2009 flood, which showed extreme attenuation, had stage predictions ranging from 0.0 to 1.11m above the actual measurements. For the March 2013 flood, the NWS released warnings that predicted stage height for a single day, five days in advance. The three warnings released ranged from .78 to 1.89m above the measured heights.

Discussion

Our results suggest peak flood discharge in the Suwannee River downstream of the Cody Scarp is dependent on groundwater heads immediately before a flood. Furthermore, we found that when floods occur after prolonged drought periods that lower groundwater heads, transient aquifer storage can result in substantial flood peak attenuation in the Suwannee River Basin.

The relationship between antecedent groundwater heads and flood peak attenuation most likely reflects a combination of hydraulic gradient between the river and the aquifer during floods and the magnitude of storage that is available in the vadose zone. When groundwater heads are low before a flood, runoff from the upper basin during floods increases river stage more rapidly than local infiltration of rainfall can increase groundwater heads. Consequently, hydraulic gradients between the river and aquifer reverse during the flood event, leading to river water flowing into the aquifer via conduits, where it is stored temporarily to reduce flood peaks. (Alberic 2004, Gulley et al 2013, Zhou 2007) For example, during the April 2005 flood, transient aquifer storage attenuated peak discharge by 15% between Ellaville and Branford.

In contrast, when groundwater heads are high, hydraulic gradients between the river and the groundwater are reduced and less flood water flows into the aquifer. For some low magnitude floods, river stage never increased above water table elevations, and consequently, groundwater inflow to the river during floods increased flood peaks. For example, during the February 2006 flood which had above-average antecedent well elevation, peak discharge increased by 8% between Ellaville and Branford.

In addition to antecedent groundwater heads, the steepness of the hydrograph and the magnitude of the flood also appear to have some influence on the degree of flood peak attenuation. Regarding the eleven floods with antecedent well and stage data, the eight attenuating floods had an average peak discharge of 682 m^3/s at Ellaville whereas the three non-attenuating floods only had an average peak discharge of 361 m^3/s. The stage height ratios (peak/antecedent) also differed, with the attenuating floods increasing stage by an average factor of 3.3 and the non-attenuating floods increasing by an average factor of 1.5. The larger floods increased stage height to the point where the hydraulic gradient switched directions, from groundwater flowing into the river to river water flowing into the aquifer. The non-attenuating floods had lesser stage increases which did not create significant reverse gradients.

The importance of hydraulic gradients between the river and the aquifer, and not just antecedent groundwater heads, is most apparent when comparing the April 2005 and April 2009 events. These events were the two largest floods in our record and appear as outliers when plotted with other floods (Fig 5A, 6A). Indeed, the large magnitude of these two April floods may explain why they have different relationships with antecedent groundwater heads than smaller floods. The April 2009 flood had a peak discharge of 1,597 m^3/s of discharge at Ellaville and the April 2005 had a peak discharge of 1,132 m^3/s at Ellaville. During April 2009 flooding, groundwater heads were 57% below average and river stage was 82% below average. Discharge ratio during this flood was 0.74, corresponding to a 26% attenuation in peak discharge (413 m^3/s) between Ellaville and Branford. While flood peak attenuation is generally predicted for floods that occur during lower antecedent groundwater heads, the April 2009 event showed far greater attenuation than other events that occurred with similar antecedent groundwater heads. This greater attenuation is due to the steeper hydraulic gradients between the river and the aquifer during these very large flood events. Indeed, steep increases in hydraulic gradients between the river and the aquifer allowed the April 2005 to be highly attenuated (ratio of upstream to downstream discharge was .85), even though the antecedent groundwater heads were above average, with water table elevation in the well 22% and river stage 8% greater than average.

When the two outlier April floods are removed in Figures 5B and 6B, the goodness of fit (R^2) becomes .85 for well elevation and .86 for river stage, meaning both data sets are nearly identical in terms of fit. However, when river stage is graphed for all twenty floods identified in the study (Fig 6C), the results initially suggest a weaker correlation, as the goodness of fit becomes (R^2) .54.

There were two months during the study period that experienced multiple flood peaks, in March 2008 and February 2010. In both cases, the time apart between flood peaks was only 12 days. Neither of these secondary floods had corresponding antecedent well data. The second flood in each case was removed from the stage vs discharge ratio plot (6D), as we felt that the short timespan between flood peaks in these cases did not allow for conditions in the system to stabilize and allow for good data. By removing the above-mentioned April floods as well as these two floods, the goodness of fit improved to .77.

Flood Prediction

Most flood prediction models predict downstream flood magnitudes using only upstream discharge and rainfall. While this approach works well in many basins such as those with confined aquifers, it does not consider the potential impact of transient aquifer storage on flood magnitudes.

Five floods had NWS stage warnings released; each of these floods had discharges of over 700 m^3/s at Branford. Three of the five (Mar 2003, Oct 2004, Apr 2005) had warnings that were very accurate, +/- 0.26m between predicted and measured stages. The two most recent floods (April 2009, March 2013) had more inaccurate predictions, with both failing to account for flood peak attenuation. Stage heights were predicted at over 1 meter higher than what occurred during the April 2009 flood, and 1.89 meters higher than measured stage for the March 2013 flood.

This analysis shows that flood predictions for this portion of the Suwannee River are inconsistent. For flood predictions to be the most useful, they need to be both accurate and timely. Predictions leading to alerts, evacuations, and prevention methods such as sandbag deployment can save lives and property if done correctly, but can waste money and lower the population's confidence if the prediction is overly inaccurate. False alarms can be frustrating and costly, and increase the risk that people will ignore future warnings that may be more accurate (Schumann et al 2011).

Given the strong correlation between antecedent groundwater heads and flood peak attenuation in the Suwannee River, results suggest that models could be improved by incorporating antecedent groundwater head information. This additional variable would allow for greater prediction accuracy, as it more closely models the processes occurring during floods in the Suwannee.

Having a larger stage analysis of twenty events is useful because river stage data is more prevalent in many locations, with smaller data intervals. In systems with a strong correlation between groundwater and stage, the latter can be used for more effective flood modeling. Stage data is often collected by high resolution equipment and telemetered, while well data is commonly collected by hand and at spaced or irregular intervals. If groundwater head data were more consistently and frequently collected, both variables could be used more effectively in flood predictions.

One concern with using stage over a long period is that the shape of the river channel may change due to large flood events. During large floods, scouring of the river channel changes cross-sectional areas and discharge capacities, which can affect stage measurements. However, Mossa and Kowinsky 1997 found that the Suwannee's tough limestone bedrock strongly resisted scouring, with sediments flushed away were replaced within 1-2 months; therefore scour was not considered to be a major factor in altering discharges and stage heights.

Implications for aquifer processes

Understanding controls on transient aquifer storage of floodwaters is important for understanding karst ecohydrology in aquifers as well as potential pollution pathways. Conduits allow floodwaters to travel much further into aquifers during bank storage events than non-karst aquifers (Baffaut and Benson 2009, Personne et al 1998, Herman et al 2008, Katz et al 1997, Ha et al 2008). Consequently, pollutants that may be in rivers during floods are more likely to be introduced to aquifers in floods that occur when water tables are low, such as after droughts, than when water tables are high. Where pollutants are transferred from conduits to the groundwater matrix, they may remain inaccessible, locked into deeply transported sediments and pore spaces until another flooding event causes them to be flushed out of the system (Baffaut and Benson 2009, Herman et al 2008, Martin and Screaton 2001).

Exchange of floodwaters and aquifers during floods can also be beneficial. In the Upper Suwannee River basin, there is an excess of nitrate (NO_3) in the groundwater due to heavy agricultural activities. This water infiltrates through sinkholes and fractures, or enters the groundwater through spring reversals during flood events. However, the spring reversals actually help remove the NO_3 by increasing chemical reactions among bacteria that digest it (Katz et al 1997). In addition, these reversals bring outside sediments, nutrients, oxygen, and dissolved organic carbon into cave and conduit ecosystems that they need to survive and could not otherwise exist without (Bonacci et al 2009).

Conclusions

This study determined that in a karst environment, a strong connection exists between antecedent groundwater heads and flood peak attenuation in the Lower Suwannee River. River stage, groundwater levels, and discharge ratios for an eleven year period were used to model the relationship between groundwater heads and attenuation. A strong, positive, linear relationship between antecedent groundwater heads, represented by stage and well elevation data, and the discharge ratio of Branford/Ellaville, downstream/upstream, occurs in this catchment. Antecedent groundwater heads control whether a flood will attenuate or not, while spring reversals and conduit systems provide a mechanism for river water to flow deep inside porous and permeable limestone aquifers, allowing for increased storage in the aquifer matrix. Understanding spring reversals and transient aquifer storage is paramount in understanding how and when pollutants and nutrients can enter karst aquifers.

Current flood prediction models do not take into account interactions between surface and groundwater, leading to predictions of varying accuracy for the basin, which can have negative social and economic impacts. By understanding how these interactions affect flood peak attenuation, they can be incorporated into future flood models to increase accuracy and public trust of forecasts and warnings.

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