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Effects of Precipitation on Groundwater Level in an Urban Watershed

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Abstract

Groundwater is an important aspect of a watershed, as it is a reservoir for the storage of water. It both releases water to the surface in dry periods and absorbs excess water in wet periods. Precipitation provides surface water that is then absorbed to replenish groundwater. The specific purpose of this research was to determine the recharge rate of the water table after a rainfall event, with a goal to also develop a framework for long-term monitoring of the water table along an urban stream in Lynchburg, Virginia, and to establish baseline groundwater data before a dam is removed from the stream. The groundwater at the study site was monitored over the course of five months using automatic water level sensors in wells. Precipitation data were obtained from the City of Lynchburg's rain gauges. Recharge rate was measured as the lag time between precipitation and groundwater rise. Graphs of the data showed groundwater fluctuation patterns that reflected precipitation events, while the lag times varied with changes in amount, intensity, and duration of precipitation. The short-term success of this research means that this methodology will be a viable way to monitor groundwater along Blackwater Creek in the long term, which will be useful in tracking changes to the watershed as College Lake is removed and new wetlands are created.

Key Words: *groundwater, water table, wells, Blackwater Creek, College Lake, dam removal*

Introduction

Water is vitally important to the existence of life on Earth. It covers over seventy percent of the Earth's surface, most of which is salt water contained in the oceans. Of the three percent of water that is actually fresh water, well over half of that is frozen in glaciers and therefore inaccessible as drinking water (Shiklomanov 1993). The surface water found in lakes and rivers only makes up about 0.27 percent of total fresh water. The second-largest category of fresh water is contained underground as groundwater, making up about 30 percent of the total (Shiklomanov 1993). Groundwater is underground water found in many locations that fills up the pore spaces in rock and soil layers (Harter 2003). The depth below the ground surface to the top of the groundwater, known as the water table, can vary greatly based on many factors, including precipitation, surface water, and soil characteristics (Harter 2003). The level of the water table plays a significant role in the accessibility of the groundwater and how it interacts with surface water.

There are two distinct types of groundwater. First, there are bodies of groundwater that are found deep underground that have no real connection to surface water, as they are enclosed under a layer of rock. This type of groundwater is known as a confined aquifer, and is typically accessed for drinking water wells or agricultural irrigation because it is a constant and reliable source of water that does not rely on precipitation (Harter 2003). The second type of groundwater, which does share a significant hydrological connection with the surface, is known as unconfined, and is the focus of this project. Unconfined groundwater, in areas with a shallow water table, exhibits frequent fluctuations in relation to environmental factors such as precipitation (Harter 2003). This is important because shallow, unconfined groundwater plays an important role in controlling stream flow and saturation of wetlands (Duval and Hill 2006). Unconfined groundwater is more readily accessible near the surface in locations with frequent precipitation and nearby surface water like lakes, rivers, and streams, with which it shares a hydrological connection. This connection is important because it allows groundwater to act as a reservoir for the storage of excess water that the surface cannot handle all at once after a precipitation event. A shallow water table that is easily accessible allows for the hydrological connection to be studied to gain a better understanding of the watershed system.

A common place to find an accessible shallow water table is adjacent to bodies of surface water. Groundwater near lakes and streams often follows a distinct pattern, as long as the soil is capable of containing water. Along the banks, the water table is at the same level as the surface of the water in the channel or lakebed. As the distance from the edge of the water body increases, the depth of the water table below the surface increases at a rate that varies based on the hydrological conditions of the area. For example, the depth of the water table will usually begin to increase only a short distance from a stream flowing through a mostly dry area, while it will typically remain at a very shallow depth surrounding a pond in the middle of a marsh.

These conditions can change based on the climate during different seasons, and are most significantly impacted by precipitation. During periods of high flow in a stream, some water from the stream seeps through the banks and into the surrounding groundwater. This is known as bank seepage, which creates a positive stream-to-groundwater gradient (meaning that there is a higher level of water in the stream than in the ground at the banks) which refills or “charges” the groundwater near the stream (Duval and Hill 2006). This is reversed in periods of very low flow, to the point where the stream is fed predominantly by groundwater seepage into the channel. This allows for a more consistent flow of water in the stream channel, which protects the stream ecosystem and keeps it from running dry in times of lower precipitation. In times of drought and extremely low flow, it has also been noted that groundwater will slow its discharge into a stream in order to preserve and stabilize the high water table, which prevents the riparian soil from drying out completely (Szilágyi et al. 2007). This helps stabilize the ecosystem by maintaining sufficient soil moisture for riparian vegetation, which is instrumental in preserving the structure of stream banks.

Since groundwater is used and discharged in different ways, it needs a reliable source of recharge in order to keep from running dry. This is, of course, precipitation. When water falls from the sky and hits the surface, it can take different courses based on a variety of factors, including surface permeability and the amount and rate of rainfall. When rain falls on an impermeable surface like a road or parking lot, it cannot enter the ground so it flows as runoff until it reaches a body of water. If it travels across enough permeable soil and is slowed down enough, it will instead infiltrate into the soil. Large amounts of precipitation at rapid rates are too much for the ground to handle, as infiltration cannot occur as fast as rain is capable of falling because the water is slowed down by soil particles and the limited amount of pore space available. Rainfall that greatly exceeds infiltration capacity flows over the surface into creeks and rivers, sometimes causing flash flooding if stream channels cannot contain all that water. A previous study of precipitation intensity found that precipitation events of over 10 mm in one day are most instrumental in the recharge of groundwater (Owor et al. 2009). This is mainly because lesser precipitation amounts are typically spread out enough between runoff, plant consumption, and moistening the soil that barely any of the water actually reaches the water table. This project seeks to expand upon that previous research and study the effects of different amounts and intensities of precipitation on the water table level along a stream.

More specifically, this project studies the lag time between precipitation and water table rise based on precipitation. A previous study conducted from 2001-2004 monitored the relationship between precipitation and groundwater in the process of creating a mathematical model for groundwater fluctuation, but this study did not focus on lag time (Park and Parker 2008). That study used daily precipitation and groundwater measurements, effectively negating lag time which would be more effectively measured on an hourly basis (Park and Parker 2008). This project focuses on the hourly relationship between precipitation and groundwater fluctuation in order to study the lag time more closely and interpret any hourly patterns it may follow. This research takes place in the riparian area upstream of an urban reservoir, which will soon undergo a stream restoration project to create a new wetland habitat after removal of the dam that establishes the reservoir. Monitoring the rise and fall of the water table in relation to precipitation will provide insight into how this watershed handles precipitation and runoff, and set the stage for future research regarding the effects of the dam removal on this stream and its surrounding groundwater. This research will be useful in the restoration efforts of creating a wetland area, as wetlands rely on a high water table to function and flourish as an ecosystem. It will also be useful in monitoring the efficacy of the wetland in flood mitigation by absorbing water during periods of intense rainfall.

Methods

Study Site

Blackwater Creek is located in Lynchburg, Virginia in an urban watershed to the southwest of the University of Lynchburg (Figure 1). It is dammed under U.S. Route 221 at 37°24'05.9"N, 79°11'02.2"W, creating College Lake that is owned by the University of Lynchburg. The dam was built in 1934 to create the lake, with an original area of 18 hectares and depth up to 9 meters (Newman et al. 2006). Over the years due to sedimentation, the water level in the lakebed has lowered to a maximum depth of less than 6 meters as of 2002, and now the lake is much smaller than it used to be, with a 2002 study finding the area to be less than 8 hectares (Newman et al. 2006). In 2018, a substantial rainfall event of around 17 cm of rain caused the lake to overtop the dam, flooding the neighborhood downstream (Shahady and Cleary 2021). As a result of this, the City of Lynchburg (owner of the dam) has decided to remove the dam in 2022 over safety concerns. The goal is to convert the lakebed and that portion of Blackwater Creek into a functional wetland.

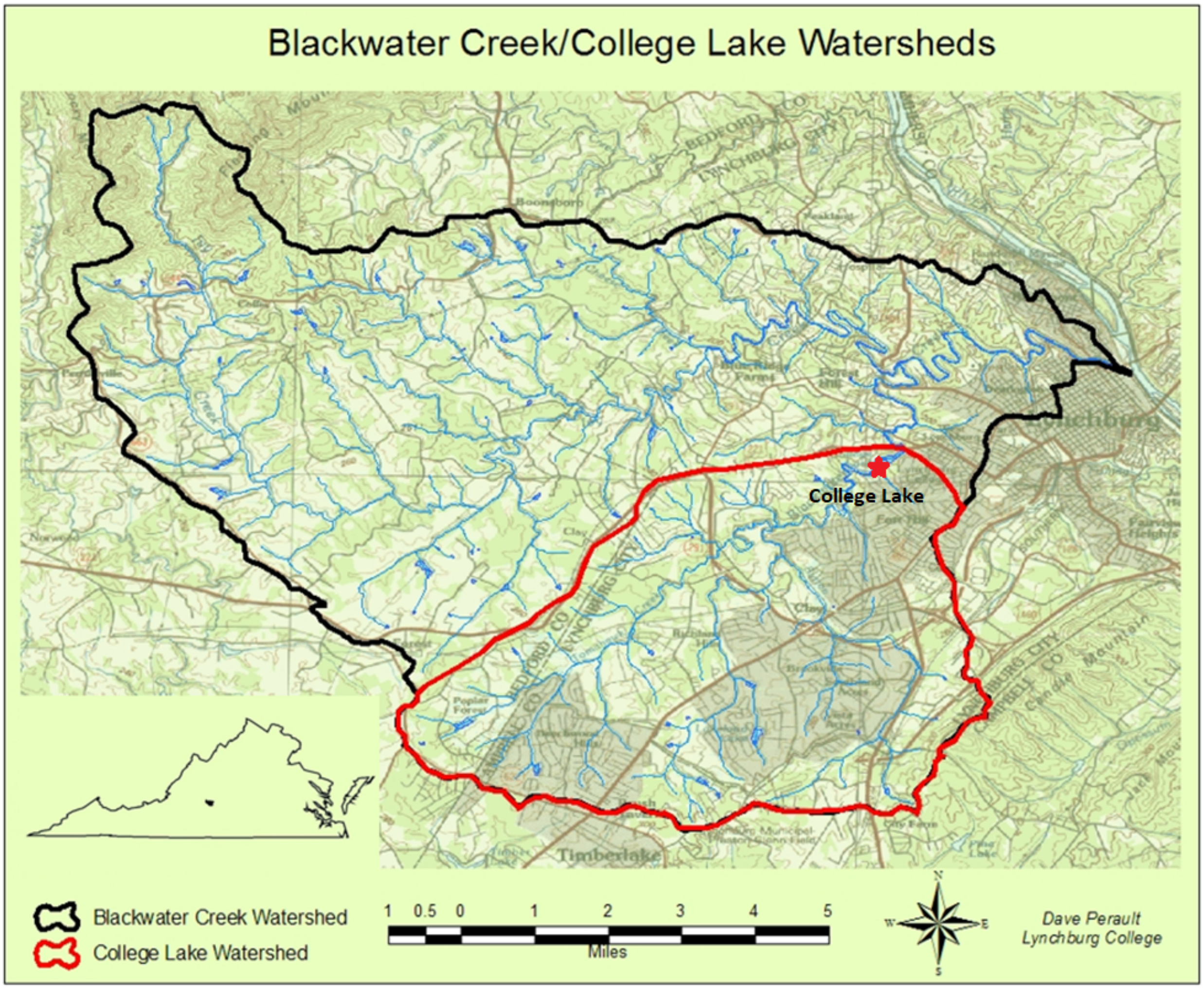

Figure 1. Watershed map. Map of the overall Blackwater Creek watershed, as well as the smaller College Lake watershed it includes (Perault 2021).

The Blackwater Creek watershed, especially the College Lake portion, is significantly urbanized. The higher the percentage of impervious surfaces in a watershed, the more the streams in that watershed will suffer from excess runoff and will struggle to handle the increased flow. The portion of the Blackwater Creek watershed that feeds into College Lake is 67.8% urban, with 23% of all groundcover being impervious surfaces. These numbers are substantially higher than the rest of the Blackwater Creek watershed that is more rural, with only 24.9% urbanization and 5.9% impervious surfaces (Shahady and Cleary 2021).

Data Collection

Data for this project were collected using four groundwater monitoring wells that were installed by hand in Summer 2020 and used for previous research (Figure 2). The wells are made of steel pipe that is 2 inches in diameter, connected to a perforated well head and covered with Onset HOBO Well Caps. The wells are 9 feet in length, and all reach slightly different depths depending on topography but the average depth is around 7 feet below the surface, leaving about 2 feet of the well exposed above ground (Figure 3). The wells were installed along linear transects crossing Blackwater Creek upstream of College Lake, so that wells are on either side of the creek (Figure 2). Transect 1 has four wells, two of which were used for this project, and Transect 2 has two wells.

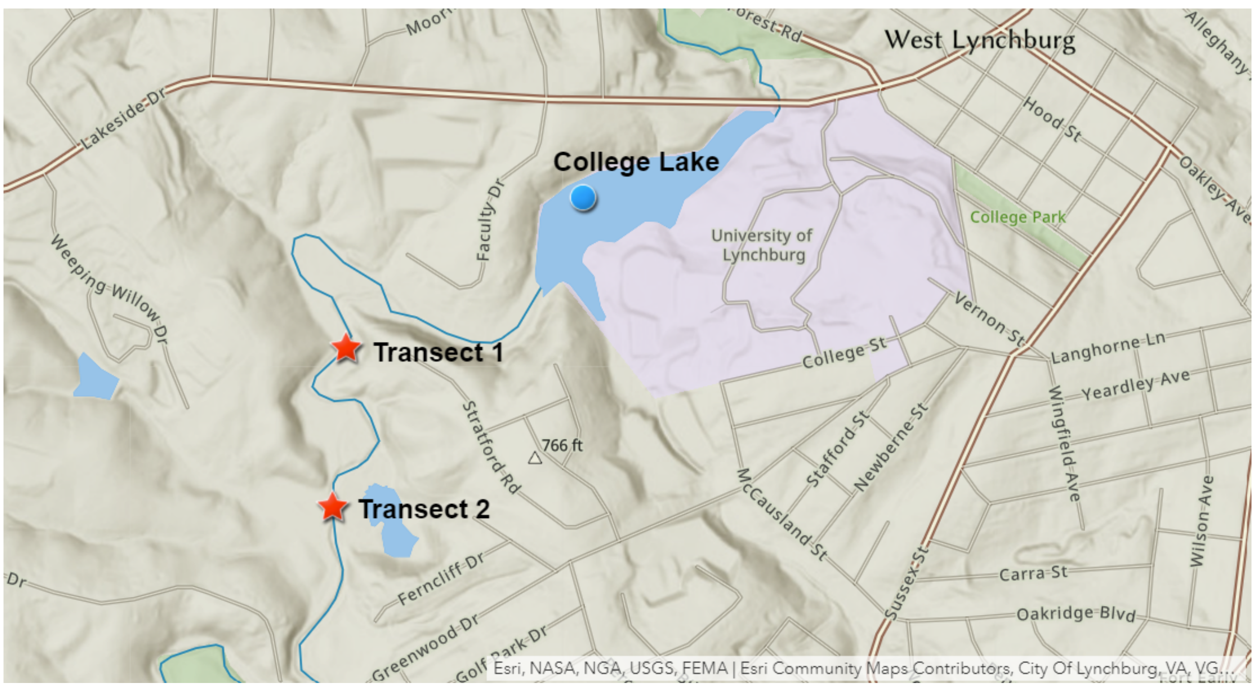

Figure 2. Transect Locations. Locations of the well transects along Blackwater Creek in relation to College Lake.

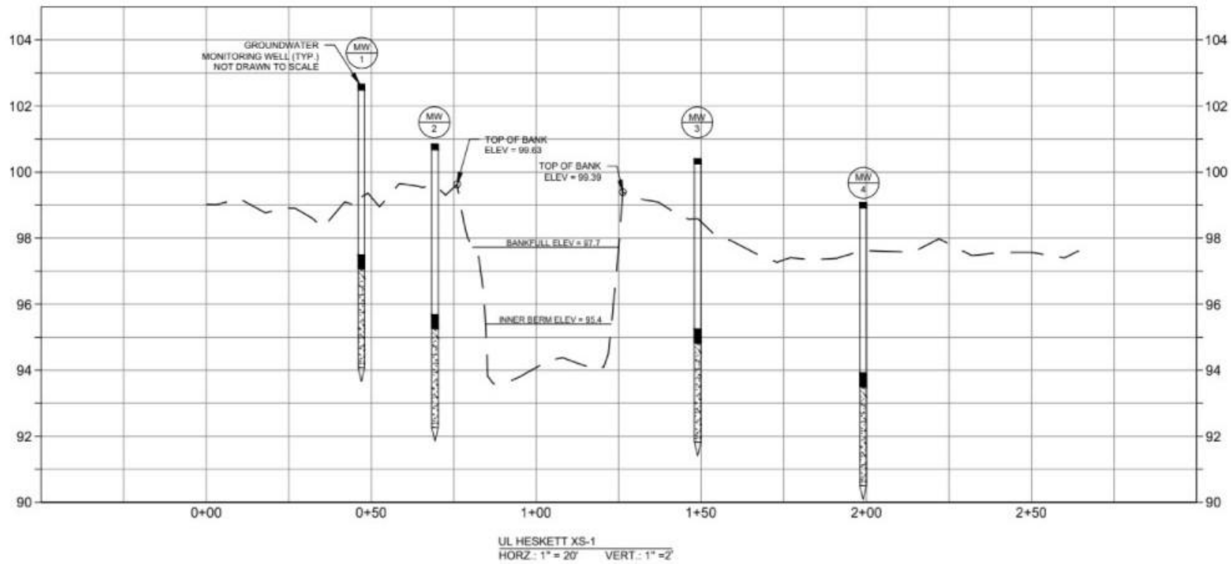

Figure 3. Cross-section of Transect 1 showing the topography and the elevation of the wells in relation to each other. Cross-section locations are approximate, and elevation measurements are in relation to a benchmark elevation assumed to be 100 feet. Well 2 and Well 3, which are closer to the stream, were used to collect data for this project. (Heskett 2021)

Upon initial setup for data collection for this project (October 6, 2021 for Transect 1, and October 21, 2021 for Transect 2), a reference water level was measured using a Solinst Model 101B Water Level Meter. Onset HOBO MX2001 Water Level Loggers were deployed in the two wells closest to the creek banks in each transect, for a total of four loggers. Loggers were deployed in wells labeled 2 and 3 in Transect 1, and 1 and 2 in Transect 2. These loggers were set up according to the instructions provided in the user manual. Loggers came with cables that are five meters in length, which needed to be folded over and secured at the proper lengths so that the sensor ends would sit just above the bottoms of the wells, ensuring that the sensors would always be able to read water depth unless the wells ran dry. Initial setup for the loggers was done using a mobile phone connected through Bluetooth on the HOBOconnect app. Setup involved naming the individual loggers, which was done according to their location in each transect, and inputting the reference water level that was taken right before the loggers were deployed. Logging interval times were set to take hourly readings. Once the loggers were installed, the well caps were closed to secure and protect the loggers.

Groundwater level data was collected in the field on March 1, 2022 using the HOBOconnect app on a mobile device. Once connected to each individual logger, data was extracted in the app as a .hobo file, then uploaded to Google Drive. With a computer, data files were downloaded from Google Drive and then opened with Onset HOBOware Pro software (version 3.7.23), where the water level readings from each individual logger were then graphed. Precipitation data was obtained from the City of Lynchburg. Hourly data were collected from a rain gauge located just over two miles upstream of the wells along Wards Ferry Rd in the Blackwater Creek watershed from October 1, 2021 through March 1, 2022 (Figure 4).

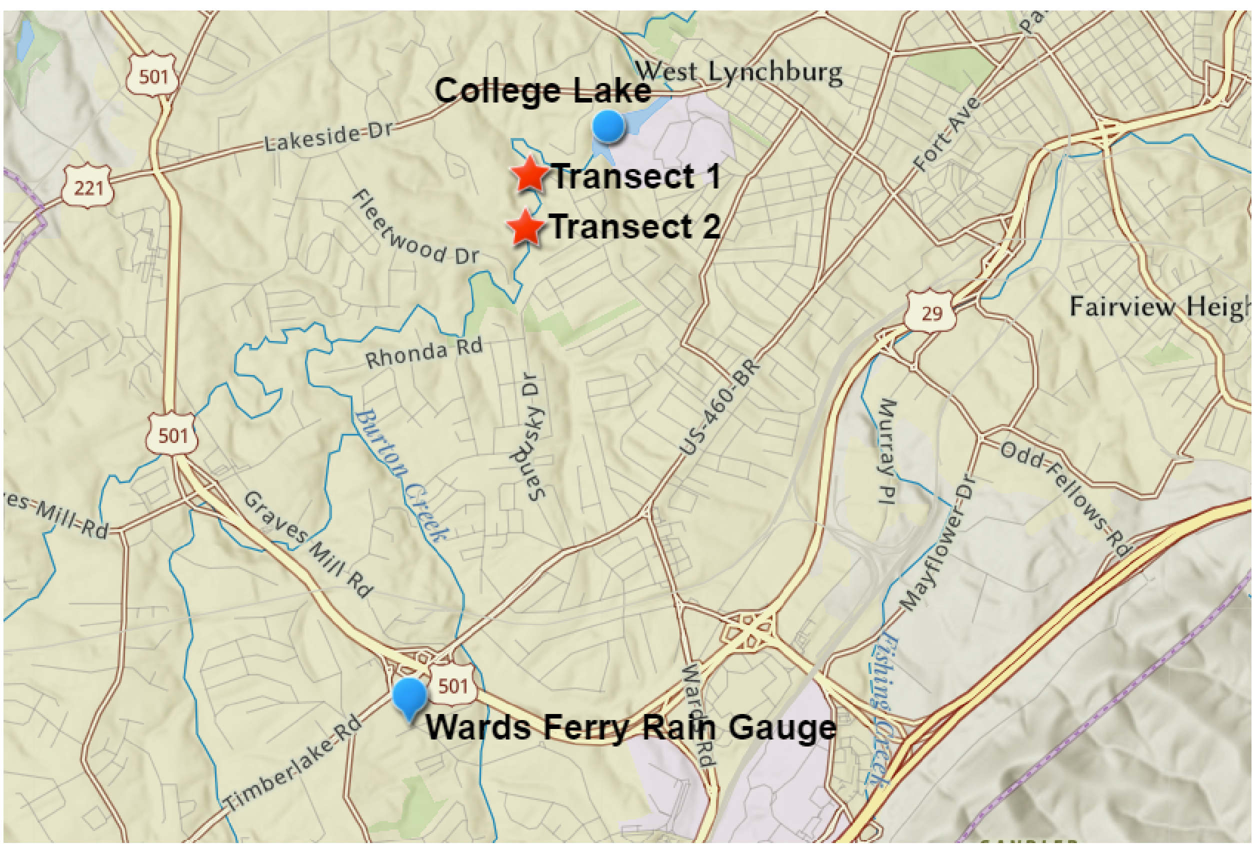

Figure 4. Rain gauge location in relation to wells. Location of City of Lynchburg's rain gauge used for precipitation data for this project, located on Wards Ferry Road near the intersection of US-501 and US-460-BR.

Data Analysis

Groundwater data was graphed along with the precipitation data in order to visualize the relationship between precipitation and groundwater level fluctuations. The lag time between precipitation peaks and water table peaks was calculated based on the data and what is shown in the graphs. There were a few minor issues with the reference water levels in the data not being the same as what they were set at initially, but that was corrected by making the first recorded measurement a negative number, and then subtracting the correct reference measurement from it twice.

Results

The results include graphs of groundwater fluctuations at each separate well (Figures 5 and 6), and then data from all four wells graphed together (Figure 7), which was then used to calculate the average groundwater level. The average groundwater level is then graphed along with precipitation in order to allow interpretation of the relationship between groundwater and precipitation (Figure 9).

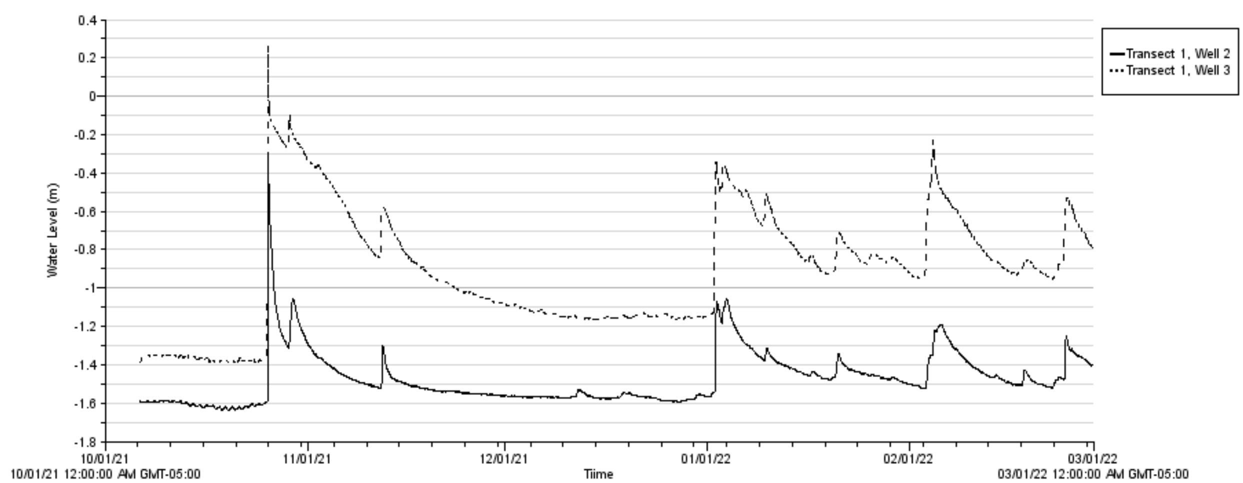

Figure 5. Groundwater measurements along Transect 1. Groundwater level (m) was recorded hourly from October 6, 2021 until March 1, 2022.

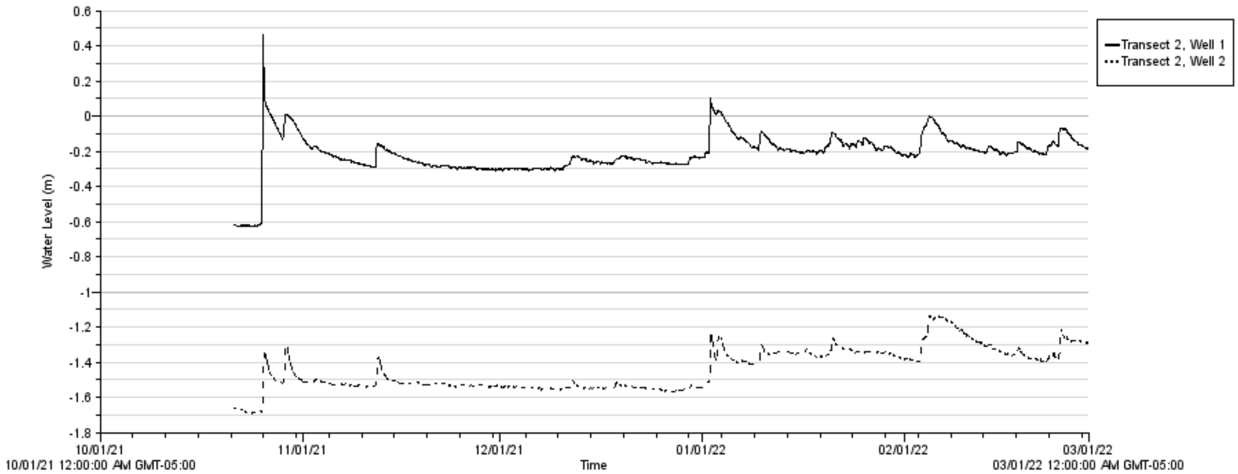

Figure 6. Groundwater measurements along Transect 2. Groundwater level (m) was recorded hourly from October 21, 2021 until March 1, 2022.

Figure 5 shows the change in groundwater level over time in each measured well along Transect 1. There is a high peak on October 25 around 10:00pm, in which the water level in Well 3 was actually recorded as being 0.25m above ground level, indicating that there was surface water present outside of the creek. After that peak, the groundwater level decreases overall with a few small spikes until January 2, where it spikes up again rapidly and then fluctuates up and down more frequently over the next two months. Figure 6, showing the groundwater level in the two wells along Transect 2, looks very similar to the pattern exhibited in Figure 5. Transect 2 Well 1 recorded the presence of surface water at the same time as Transect 1 Well 3 did, measuring water 0.46m above the surface. When the graphs are overlaid all together, it is evident that the groundwater system follows the same pattern across both transects (Figure 7).

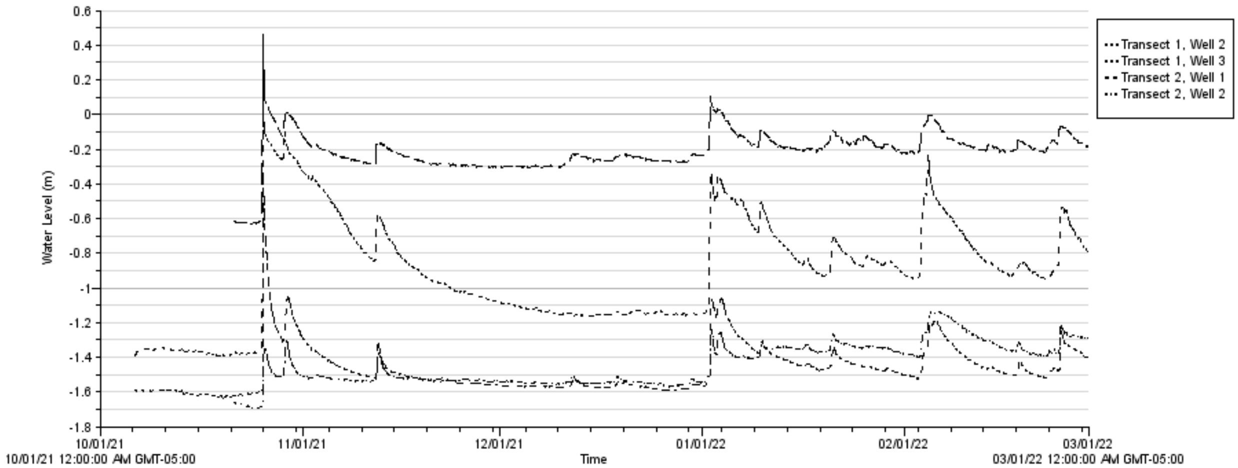

Figure 7. Groundwater measurements along Transects 1 and 2. Data from each transect is graphed here to show consistency in timing of fluctuations.

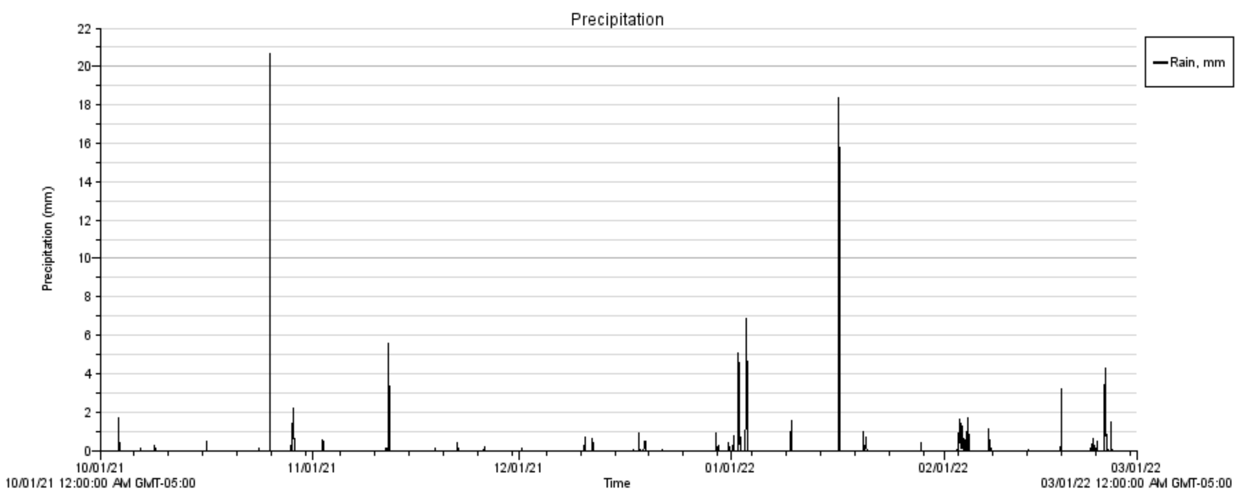

Figure 8. Precipitation measurements. Precipitation (mm) was recorded hourly from October 1, 2021 until March 1, 2022.

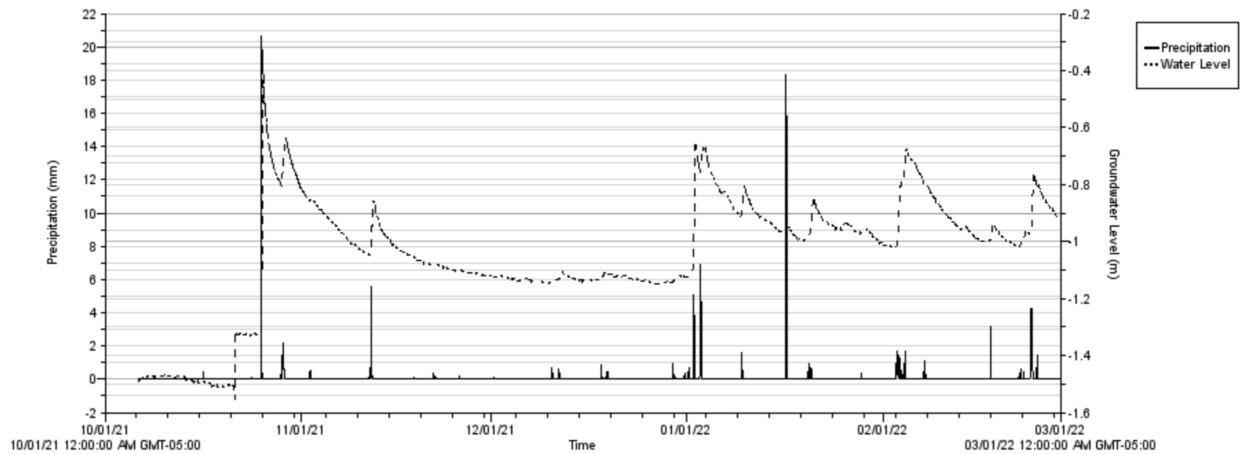

Figure 9. Precipitation and average groundwater. Graph of hourly precipitation amounts along with the average groundwater measurement across all four wells.

The average level of all the groundwater measurements was calculated and graphed as an overall trendline for the groundwater fluctuations. This was plotted in Figure 9 along with the precipitation measurements from Figure 8. The graph shows that high peaks in groundwater levels correspond closely with precipitation. To further analyze this apparent pattern and to determine if there is a pattern related to lag time, some data segments showing different types of precipitation events will be broken into separate graphs covering shorter periods of time. These will include one brief but intense precipitation event, one event with two moderate periods of precipitation, and one very light precipitation event spread out over a long period of time.

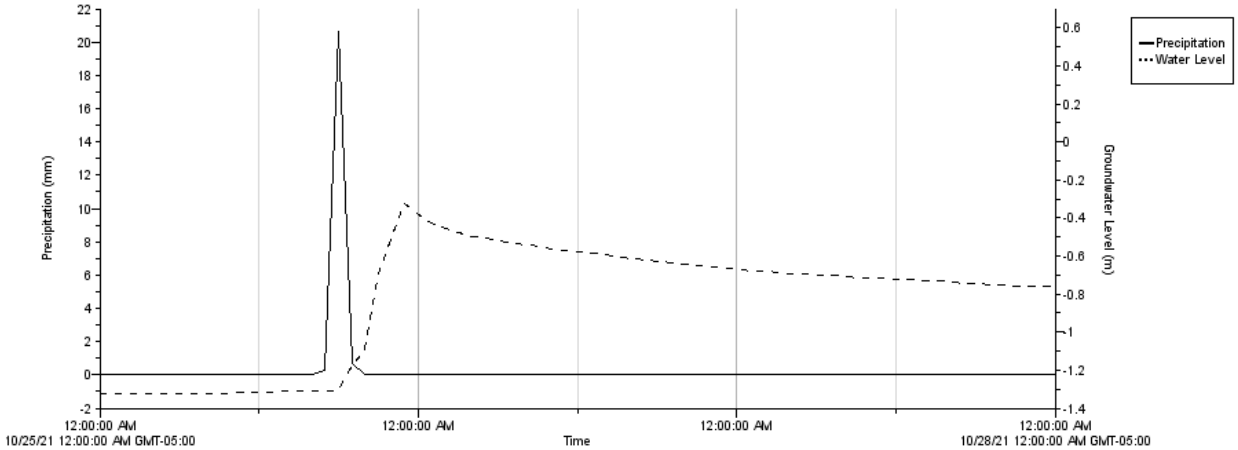

Figure 10. Precipitation and groundwater from 10/25/2021 to 10/28/2021. A segment of data showing groundwater response to precipitation.

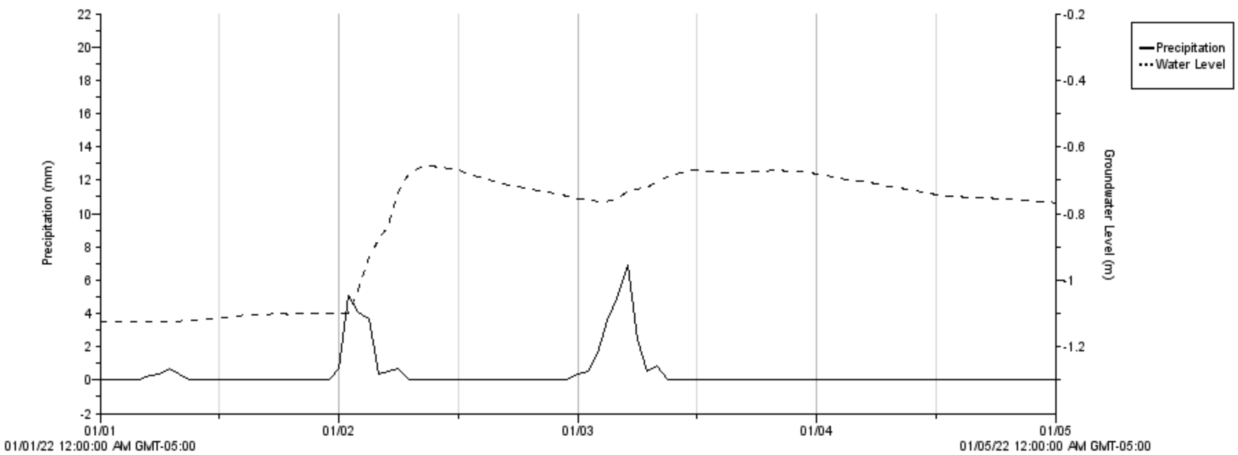

Figure 11. Precipitation and groundwater from 1/1/2022 to 1/5/2022. A segment of data showing groundwater response to precipitation.

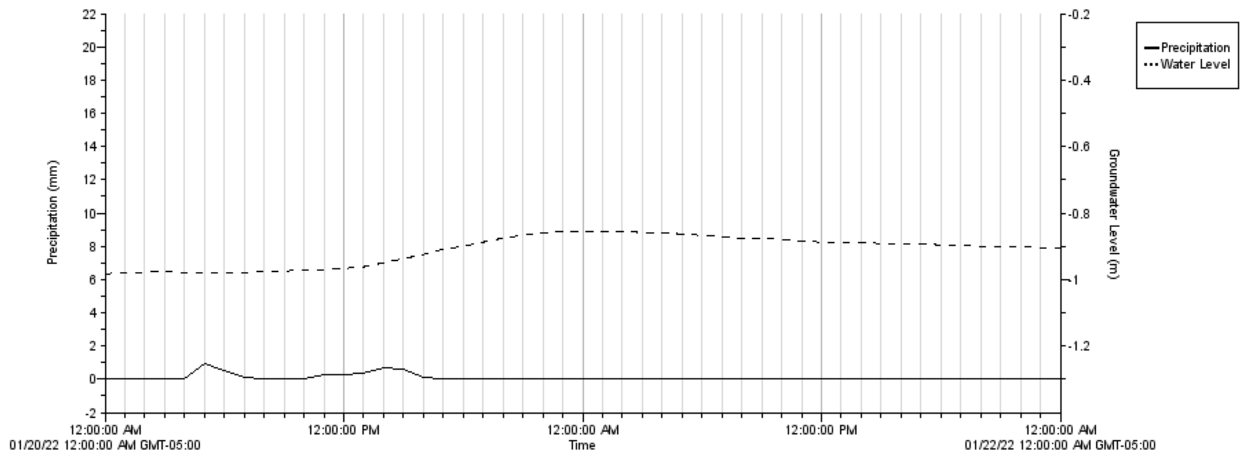

Figure 12. Precipitation and groundwater from 1/20/2022 to 1/22/2022. A segment of data showing groundwater response to precipitation.

Figure 10 shows a precipitation event in which a large amount of rain fell in a short period of time. At its peak at 6:00 pm, 20.66 mm of precipitation was measured within that hour, and over a 3-hour span, 21.66 mm of rain was recorded. The groundwater level rose quickly beginning at 6:00 pm, and peaked at 11:00 pm, which is a lag time of 5 hours between peak precipitation and peak groundwater rise. Figure 11 shows two rainstorms that were not as intense as the last one. The first one totaled 15.06 mm over a 7-hour period, peaking at 5.08 mm at 1:00 am on January 2. Groundwater also began rising rapidly at 1:00 am and then peaked at 9:00 am, for a lag time of 8 hours. The next round of precipitation began at 11:00 pm on January 2, peaked at 5:00 am January 3 with 6.86 mm of precipitation, and ended at 9:00 am. The total was 21.76 mm over a 10-hour period. The groundwater level was already elevated from the recent precipitation, but it began to rise again at 5:00 am, 6 hours after precipitation started, and peaked at 11:00 am, 6 hours after the peak precipitation. Finally, Figure 12 shows a slow, more steady rainfall with a low precipitation total of 3.87 mm over a 12-hour period of time from 4:00 am to 4:00 pm, with the peak hourly precipitation only reaching 0.95 mm at 5:00 am. Groundwater level begins to increase at a very slow rate at 9:00 am and then begins to increase slightly more rapidly at 1:00 pm, finally reaching a rounded peak at 1:00 am the next day. The groundwater level increase began 5 hours after the start of the precipitation, but it did not begin to make significant hourly changes until 9 hours after precipitation began. The peak water table level was reached 9 hours after precipitation ended and 20 hours after peak precipitation.

Discussion

Relationships Between the Wells

The peaks in water table rise look very similar across all four wells (Figure 7), which shows that the water table in the overall study area is operating as one unit, not as independent sections. Differences in groundwater fluctuation amounts can be attributed to the surface conditions at each location, as well as the depth of the wells in relation to the water table. Transect 2, Well 1 is somewhat of an outlier in relation to the other three wells as it sits in more of a wetland area than the others do. Therefore, it has a much higher water table that is near the surface at normal levels, while the wetland area around it contributes to more minor water table fluctuations than the other wells. The pattern exhibited at this location seems promising as a predictor of the efficacy of expanded future wetlands as a part of stream restoration efforts, because less-drastic fluctuations imply that the wetland area is successful at slowing down flow changes in the watershed system and storing water that may otherwise make it into the stream all at once.

Interpretation of Relationship between Groundwater and Precipitation

Figure 9, comparing precipitation and groundwater fluctuations, shows a definite relationship between the two variables, but description of the differing lag times in figures 10, 11, and 12 suggest that the intensity and duration of precipitation also has a substantial impact on how long it takes for groundwater to respond. Brief but heavier precipitation such as that shown in Figure 10 caused a rapid change in groundwater level that peaked only 5 hours after peak precipitation. Before this precipitation event, there had been very little precipitation (a total of only 3.56 mm since the beginning of the month) so the groundwater was likely at a relatively low state. Unfortunately, there was not much historical groundwater data available to compare to, so that is only an inference based on subsequent data collected during the course of this project. This shorter lag time seems to suggest that the water table was lower than usual so it was ready to quickly accept water. The overall average level of the water table throughout the data collection period was -1.04 m, and from the start of data collection until the precipitation on October 25, the water table was averaging -1.45 m. Based on that difference, it can be inferred that the below-average groundwater level contributed to the shorter lag time and quicker absorption of the precipitation. A possible additional contribution to the short lag time is the fact that a small amount of precipitation fell the day before, which would have moistened the soil and sped up infiltration (Jeong and Park 2017).

Moderate precipitation spread out over longer periods of time, like the two events shown in Figure 11, had slightly longer lag times of 8 hours and 6 hours, respectively. For the first period of precipitation, the water table again began to rise at the same time as the peak rainfall, but this time peaked 8 hours after. This pattern corresponds with the longer duration and lower intensity of the rainfall. The rain fell and accumulated more gradually, and the slower rise of the water table mirrors that. The next period of rainfall began only 16 hours after the previous storm ended, and as such the water table was still in an elevated state. The lag time between peak precipitation and peak water table level was only 6 hours this time, likely because the soil was already saturated (Jeong and Park 2017) and therefore allowed surface water to infiltrate into the water table faster than it did in the storm the day before.

Very light precipitation spread out over a longer period of time, like the scenario in Figure 12, causes a slower change in the water table. This precipitation event lasted 12 hours, and the water table did not begin to significantly rise until the 9th hour. It took 20 hours after peak precipitation for the water table to reach a peak. The amount of precipitation from this event only totaled 3.87 mm over a span of 12 hours, so it is impressive to see that the water table was actually impacted at all, rising an average of 0.13 m across the four wells. The lag time in this instance was extended significantly because of the duration of the precipitation and the very low amount of water that fell. Had the precipitation amount been higher, the groundwater response likely would have been more rapid and also more significant.

Another aspect of water table fluctuations that is evidenced in Figure 9 is the quick downward shift in the water table after a peak. Once the water table peaks after a precipitation event, it begins to go back down within a few hours, which shows that the Blackwater Creek system has some level of equilibrium that is being targeted. Without an extended period of data collection of at least a year, it is hard to tell where that equilibrium is, but it is evident that the system is gravitating towards a certain water table level after precipitation events. The rate of the downward trend after peaks seems to correspond to the shape of the line plotting groundwater rise. The abrupt rise in the water table after the October 25 precipitation also declined pretty rapidly (Figure 10), while the decline after the January 20 precipitation was much more gradual

(Figure 12). Future long-term monitoring of the study site will be useful in making more accurate determinations about how the watershed system handles precipitation now and how it changes once the dam is removed.

Impervious Surfaces

The excessively high amounts of impervious surfaces present in the College Lake portion of the watershed most likely has some sort of impact on how the watershed system handles precipitation. A higher-than-normal proportion of runoff to infiltration caused by impervious surfaces would likely increase the time it takes for precipitation to enter the groundwater system. Future research involving a well set up further away from a creek in a more urban area of the watershed would be useful in determining how much rainwater reaches the water table in locations other than along a stream. I would predict that groundwater fluctuations in that type of location would be much less dramatic than what was measured for this project, since more of the surface water is unable to infiltrate and instead moves to a different location as surface water. Additionally, I would predict that in a very rural watershed, the differences in groundwater fluctuations along a stream and further away from it would not be as significant as they likely would be in this watershed, since more water would infiltrate into the ground instead of flowing into the streams. The water table along streams acts as a sort of buffer to maintain some equilibrium and reduce flooding hazards, but this capacity may be overworked in highly urbanized watersheds like College Lake/Blackwater Creek. The groundwater system adjacent to a stream can only handle so much excess runoff before the rest of the water flows downstream and causes flooding, whereas if the groundwater across most of the watershed is able to absorb precipitation, then the effects of precipitation on a stream and its adjacent water table will not be nearly as dramatic. This leads to better overall stream health, as the channel is not having to handle more water on a regular basis than it was originally meant to handle. The shortcomings of an urbanized watershed in regards to surface runoff can likely be mitigated somewhat with an increase in wetland areas near the stream, as wetlands are capable of slowing down surface water and allowing for increased infiltration.

Even though wetland areas can be useful in slowing and holding water, there can still be issues that come with them. Riparian soil that is highly saturated, coupled with moderate slope, leads to instability of the ground and the potential for landslides and rapid erosion (Sangrey et al. 1984). Steep slopes and saturated soil are often found along stream channels where the stream has eroded sediment away and cut a deep channel. Bank instability is a major problem involving erosion and sedimentation of water bodies, as well as the destruction of riparian habitat. As part of an urban watershed, Blackwater Creek suffers from severe erosion due to excessive runoff caused by impervious surfaces. The channel in the study area is very deep and boxy with steep banks showing exposed sediment, which will only erode further every time the stream rises (Figure 13). Wetland areas near the stream, as well as an overall high water table in the area, leads to soft soil that is unstable in flooding conditions and is therefore subject to erosion and channel incision. Improvements in riparian vegetation will be instrumental in maintaining the structural integrity of the soils along Blackwater Creek.

Figure 13. Stream banks. Image looking upstream from Transect 1, showing steep, incised banks with exposed sediment subject to erosion. Note the trees on the far side of the bank where the sediment has washed out from under the roots, which will eventually cause the trees to fall into the creek. This is common along this stretch of stream.

<u>College Lake Dam Removal</u>

When the dam is removed from Blackwater Creek to eliminate College Lake, the groundwater system along the stream will likely be impacted in some way. As the lake acts as a large detention basin for excess water during and after heavy rainfall, I predict that the groundwater system will have to change in some way to try to absorb more of that excess water to prevent an increase in flooding. Groundwater recharge rates are faster in areas with saturated soil than areas with dry soil, even during periods of heavy precipitation (Owor et al. 2009). This is consistent with Novakowski and Gillham’s (1988) conclusions that capillary action plays a major role in the rate of groundwater recharge when the capillary fringe, which marks the bottom of the unsaturated zone and the transition into the saturated zone, is at or very near the surface. Based on these findings, moist soils with a shallow water table (such as the soils found in wetlands) play a very important role in the infiltration of runoff and the mitigation of possible flooding events by rapidly taking water from the surface before it enters or continues along stream channels. Hopefully, the constructed wetland that is planned will be able to absorb some of that water and slow down the downstream flow enough for more infiltration to occur, but with a wetland comes an elevated water table which presumably means less space for excess water to infiltrate and be stored as groundwater. There is eventually a point at which all the pore spaces in the soil are filled, meaning that the ground is completely saturated and therefore unable to take in more water. Reduction in infiltration capacity of saturated soil increases the time between rainfall and infiltration and the overall amount of infiltration (Park and Parker 2008). This could be an issue in a wetland because if the water table reaches the surface, then the wetland will begin to function more like a lake and collect excessive surface water. Surface water leads to flooding if it accumulates rapidly enough, so hopefully the design of the wetland will take that into account and be able to slow the water down and hold it for long enough for a high rate of infiltration. Because of the topography of the watershed and the creek channel directly above the lake, when the lake is drained the flow rate of Blackwater Creek will increase substantially, quickly cutting a channel through the accumulated sediment in the lakebed (Pizzuto 2020). Establishing a meandering stream path through the lakebed will help slow down the flow of water through the wetland, and establishing a community of wetland vegetation will help to further slow the flow of the creek. Furthermore, maintaining flat topography as much as possible will be a major aspect of the restoration issue. There will be a drop in elevation once the dam is removed, which will increase flow rate unless the channel is engineered to minimize this. Constructing terraces in the stream channel to create small drops in elevation throughout the restoration area will minimize the distance that water will fall all at once, limiting the opportunities for it to pick up speed as it flows downstream. Maintaining a slow stream flow is instrumental in limiting stream erosion and flash flooding, both of which cause issues that compound as water flows downstream (Chaplin et al. 2005). To further mitigate erosion, restoration efforts will need to include a focus on the stream banks (Figure 13), most likely through the use of reinforcement materials and added vegetation to improve the structure of the banks (Pizzuto 2020). Efforts could be made to reduce the steep angle of the stream banks, but that seems less ideal because it would involve a major disruption of the riparian zone that is already established, and likely lead to more erosion and channel incision in the future.

Baseline Data and Future Monitoring

This project was able to successfully accomplish the goal of gathering baseline data and establishing an effective methodology for long-term monitoring of the groundwater system along Blackwater Creek. Once deployed, the data loggers required no human interaction other than periodically checking on them to make sure they were still running and that the batteries had not died. The sensors are set up so that they can potentially collect data for up to 4 years without any maintenance, but it is recommended to check on them every 6 months or so to make sure the batteries still have plenty of life left in them. Periodic maintenance checks are good practice for any equipment that is left unattended, and the sensors and wells are no different. This way, if anything happens to any of the equipment, it will be less time until someone notices and is able to fix it, creating a shorter gap in data collection.

The baseline data collected for this project will be important in future monitoring of the site, especially as the dam is removed from below College Lake. The removal of the lake will likely have an impact on how the Blackwater Creek system handles precipitation, and a new equilibrium will be established. The creation of new wetlands will also likely have an impact on the precipitation-groundwater interaction, as wetlands hold water that would otherwise flow elsewhere. It will be interesting to compare it to the data collected for this project and the data collected after March 1, 2022, as the loggers were left in the wells to collect data for future research.

<u>Other Future Uses of this Research</u>

In addition to the role this monitoring system could play in studying the groundwater response to the removal of the dam, it could also be used for other future student research projects. A continuation of my research would certainly be worthwhile, especially during the period of time in which the dam is being removed and Blackwater Creek's flow pattern is altered dramatically in a short period of time. Monitoring the groundwater response during that phase, as well as afterwards, would provide insight into how the system may handle precipitation in the future. Comparing that to data collected prior to the removal of the dam could show how effective the lake was at controlling flooding, and then future data would help determine if the new wetland has similar capabilities, or if the system will need to rely more heavily on groundwater capacity as a sink for excess precipitation. The incorporation of a surface water study along with this data could also be useful, maybe as a three-variable study with precipitation, surface water, and groundwater, in order to see how much and how quickly the water level in Blackwater Creek rises after precipitation compared to what groundwater does. This could be very useful in predicting flooding impacts once an initial study is done and some baseline data for different precipitation amounts and intensities is collected. While predicting flooding does nothing to prevent it, it can provide an earlier warning to residents along the stream so that they can have more time to get to safety. This is especially useful in the case of flash flooding, which happens when heavy rain falls for a short period of time, but is enough to cause streams to rise before the water can infiltrate into the groundwater. Flash flooding is especially prevalent in urbanized watersheds like this one, where precipitation is magnified by higher-than-normal amounts of runoff. Any tools to help predict flash flooding will be useful in adding to community safety.

Another possible use of this monitoring system is for educational purposes. The goal of the dam removal project is to create a wetland area on campus, which will likely be used for education of science students, and possibly others as well. The creation of an interpretive sign about groundwater and how it plays a role in the watershed system would be a good educational tool for an important aspect of the watershed that goes unnoticed by most people since it is underground. The sign could possibly even be accompanied by another well installed in an educational area that would be open for groundwater measurements by classes or student researchers.

A further aspect of future groundwater research is the comparison to different watersheds with different ground cover characteristics. Using data from the wells along Blackwater Creek and comparing that to data collected from wells along the Big Otter River at the Claytor Nature Center, which is part of a rural watershed that has been minimally impacted by urbanization, would give a better understanding of how much the streamside water table in an urban watershed compensates for the lack of infiltration elsewhere in the watershed. This would involve the installation of a few other monitoring wells in locations away from the main stream and might be logistically difficult, but could provide very interesting results if done successfully. The groundwater along the stream and away from the stream (in an urban location in the College Lake watershed, and a rural area in the Big Otter watershed) would need to be graphed and compared to see the changes in fluctuation based on ground cover. This would show the differences between centralized precipitation impacts along a stream, as opposed to the impacts being spread throughout the watershed where water is able to infiltrate almost everywhere.

Conclusions

The groundwater monitoring system established along Blackwater Creek will be a substantially useful tool in the future stream restoration effort. Continually monitoring the rise and fall of the water table and its relationship to precipitation will help measure the overall effectiveness of the created wetland in mitigating flooding and excess stream flow. Groundwater data collected during this process can also be used to inform future dam removal projects in other locations and provide a baseline for the efficacy of replacing reservoirs with created wetlands in urban watersheds.

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