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Characterizing Groundwater Recharge and Streamflow using Stable Isotopes of Oxygen and Hydrogen

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CHARACTERIZING GROUNDWATER RECHARGE AND STREAMFLOW USING STABLE ISOTOPES OF OXYGEN AND HYDROGEN

by

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Western Michigan University, 2016

Potential changes to climate and precipitation patterns from anthropogenic influences like global climate change could have an impact on Michigan's groundwater resources. Indirectly this could have an effect on Michigan's surface waters as well, since groundwater and surface waters are intimately linked to form one system.

This investigation utilized stable isotopes of oxygen and hydrogen found in precipitation, groundwater and surface waters to better understand the contribution of different types of precipitation to recharge of a shallow aquifer in Manistee National Forest, MI. The study also examines the contribution of this shallow groundwater to streamflow in the nearby White River. When combined with various physical and chemical hydrologic approaches, the dynamics of precipitation, groundwater flow and groundwater discharge into the stream become clearer.

Samples from the different waters were collected from February 2015 to January 2016. During sampling groundwater head, stream discharge and other parameters were measured. These data provide valuable insight that will help the U.S. Forest Service better manage this natural resource.

ACKNOWLEDGEMENTS

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CHAPTER I

INTRODUCTION

Groundwater recharge and discharge

Shallow groundwater aquifers typically are water-table aquifers (Fetter, 2000). These are unconfined aquifers, the top of which mark the boundary of the water table. The water table is defined as the boundary between the saturated zone and the unsaturated zone where the groundwater pressure head is equal to atmospheric pressure. Below the water table the soil/bedrock is fully saturated, and above it the soil contains empty pore spaces and small amounts of water that either haven't percolated down to the water table yet or are adsorbed onto sediment particles.

Groundwater flows through pore spaces from areas of higher elevation to areas of lower elevation (Pinder, 2006). When precipitation events occur water is added to the system, and water typically leaves the groundwater system by being discharged into a nearby surface water body that occupies an area of lower elevation or through evapotranspiration during the growing season. Since the amount of water in the aquifer depends on the rates of recharge and discharge, it's important to identify the amounts of recharge and discharge to understand the dynamics of the groundwater system.

The type of precipitation can determine the amount and rate of aquifer recharge (Ponce, 1989). Thus, local climate patterns can cause recharge to occur during summer and fall rains or in the spring when winter snow melts. Recharge is also influenced by the amount of precipitation, how saturated the soil is prior to precipitation, the geology of the area, the amount and type of vegetation, and the depth to the water table, among other

things (Fetter, 2000). Changes to precipitation patterns will affect the recharge to the aquifer, which can then affect the amount of water in the aquifer and possibly the amount of water in nearby surface water bodies that rely on groundwater discharge.

Changes to surface water bodies due to changes in groundwater can occur if the lake or stream is a gaining stream, which is a stream that receives input from groundwater (Fetter, 2000). Groundwater in these systems leaves the subsurface at the margins and bed of the surface water body. Typically this occurs as diffuse discharge across the streambed or lake bed, but with high amounts of groundwater discharge springs may form with groundwater discharging visibly. This type of discharge is seen at the study site in this research, the headwaters of the White River. If groundwater levels become low enough due to a decrease in precipitation, the surface water may stop receiving groundwater contribution, or could start losing water back into the subsurface to make up for the lost recharge (Ponce, 1989). As a result, surface water levels can decline, or even dry up entirely. With the importance of surface water to modern society it is vital to manage the groundwater system when trying to manage the surface water since it’s all one system.

Stable isotope hydrology

Isotopes are species of an element that have the same number or protons, but a different amount of neutrons. This different number of neutrons gives the isotopes slightly different masses. This difference in mass causes the isotopes to have slightly different kinetic reaction rates, with the lighter isotopes tending to react faster than the heavier isotopes. An isotope is stable if it doesn’t radioactively decay into a different isotope over time.

Since water is composed of hydrogen and oxygen, the main isotopes studied in water are ^{16}O, ^{17}O, ^{18}O, ^{1}H and deuterium (^{2}H) (Clark and Fritz, 1997). Of these isotopes, ^{16}O and ^{1}H are the most abundant on Earth, with relative abundances of 99.797% and 99.989% respectively (Sharp, 2007). Because the relative abundances of the heavier isotopes are so small, isotopic measurements are made relative to a reference standard and reported in "delta notation," which has the equation:

$$\delta = \frac{R_{SAMPLE} - R_{VSMOW}}{R_{VSMOW}} \times 1000‰$$

where R is the ratio of heavy-to-light isotopes and VSMOW is the reference standard. It stands for "Vienna-Standard Mean Ocean Water," and represents the isotopic compositions of the oceans, where almost all precipitation is derived (Clark and Fritz, 1997). Because VSMOW is the standard, it has a δ-value of 0‰. Since isotopic variations are generally very small, they are multiplied by 1000 and reported in "per mil" increments. Typically values of waters on land are negative, indicating they are more depleted in the heavier isotopes than VSMOW. This is due to the natural partitioning, or fractionation, that occurs during phase changes of water.

As ocean water evaporates, the vapor is depleted in the heavy isotopes (Craig, 1961; Clark and Fritz, 1997). This is due to the aforementioned differences in reaction rates. The lighter isotopes fractionate into the vapor, depleting it of heavy isotopes while simultaneously enriching the original ocean water. As this vapor moves over land and condensates to form precipitation, the heavy isotopes that made it into the vapor phase fractionate into the condensation. This makes the vapor even more depleted while making the precipitation slightly enriched (although still more depleted than the ocean water it came from). Because the vapor was already depleted in heavy isotopes, this fractionation

during precipitation causes it to become even more depleted, so that subsequent precipitation events will have less and less heavy isotopes. This is what's known as the rain-out effect, and it's why areas far from their precipitation source (the oceans) tend to have more depleted isotopic values in their precipitation. In Michigan, the vast majority of precipitation comes from the Gulf of Mexico, with some slight influence from Lake Michigan (Machavaram and Krishnamurthy, 1994). This means the precipitation in Michigan tends to be more depleted than somewhere closer to the Gulf.

In temperate climates, seasonal effects can also be seen in the isotopic composition of precipitation (Clark and Fritz, 1997). Snow and winter precipitation tends to be more depleted than summer rain. Due to this difference, the relative contributions of these different types of precipitation to the amount of groundwater in a shallow aquifer can be determined (Sklash, et al., 1976). The groundwater's isotopic composition will be somewhere between the depleted snow and the enriched rains. The closer the groundwater's isotopic signature is to one of these, the more that type of precipitation contributes to recharge.

This same process can be applied to surface waters that have a groundwater component (Sklash, et al., 1976; Obradovic and Sklash, 1986; Hooper and Shoemaker, 1986). The two main sources of water for surface waters like lakes and streams are groundwater and surface runoff from precipitation. The stream's isotopic composition will be somewhere between the groundwater and the precipitation. The more groundwater contributes to stream flow the closer the stream's isotopic composition will be to the groundwater's, and vice versa.

CHAPTER II

RESULTS AND DISCUSSION

The results of this research are presented in the form of a research manuscript which has been submitted for publication to a peer-reviewed scientific journal. The manuscript has been modified slightly so it can be presented in the form of a master's thesis.

The research manuscript shares the same title as this thesis: "Estimating Contributions to Aquifer Recharge and Streamflow Using Stable Isotopes of Oxygen and Hydrogen." The study used stable isotope ratios found in precipitation (both rain and snow), groundwater in different parts of the aquifer, and stream water to determine the source of recharge to the aquifer and the baseflow contribution to overall streamflow. It combines the isotope information with electrical conductivity of the different waters and various physical hydrological measurements to confirm the interpretations of the isotope data and quantify some aspects of groundwater discharge.

The manuscript also contains information from a previous study done at this research site in May-June of 2013. This research was part of a previously unpublished undergraduate research project that was the impetus for this master's thesis.

Characterizing groundwater recharge and streamflow using stable isotopes of oxygen and hydrogen

Introduction

With the growing concern over diminishing freshwater resources and the potential impacts from global climate change on these resources, it’s important to understand the dynamics between precipitation, shallow groundwater and surface waters in order to better manage these resources going forward. This is especially important in the United States, where over a third of the population relies on groundwater for drinking water (Maupin, et al., 2014). In Michigan groundwater is even more vital, with almost half of the population using it for domestic water supply (MDEQ, 2013).

The amount of recharge to a shallow aquifer depends not just on the amount of precipitation, but also the type and rate of precipitation, the geology of the soils, the topography of the landscape, the depth from the surface to the water table and the saturation levels and infiltration capacity of the soil, among other things (Fetter, 2001). The connectedness of the aquifer to nearby surface waters is equally complex. Despite these complexities, the use of naturally occurring chemical tracers such as stable isotopes can help unravel some of the different relationships at work in the subsurface with minimal disturbance to the system. When this is combined with some empirical techniques to quantify groundwater and stream discharge, the importance of the groundwater contribution to streamflow becomes more apparent.

The White River is a groundwater-fed stream that originates in northern Newaygo County and flows to the southwest where it discharges into Lake Michigan in Muskegon County (Figure 1). The headwaters of the White River are located along Six-Mile Road in Newaygo County, Michigan. The headwaters are in Manistee National Forest

approximately 16 kilometers north of the town of White Cloud. The White River discharges into Lake Michigan near the town of White Hall, approximately 72 kilometers southwest of the site.

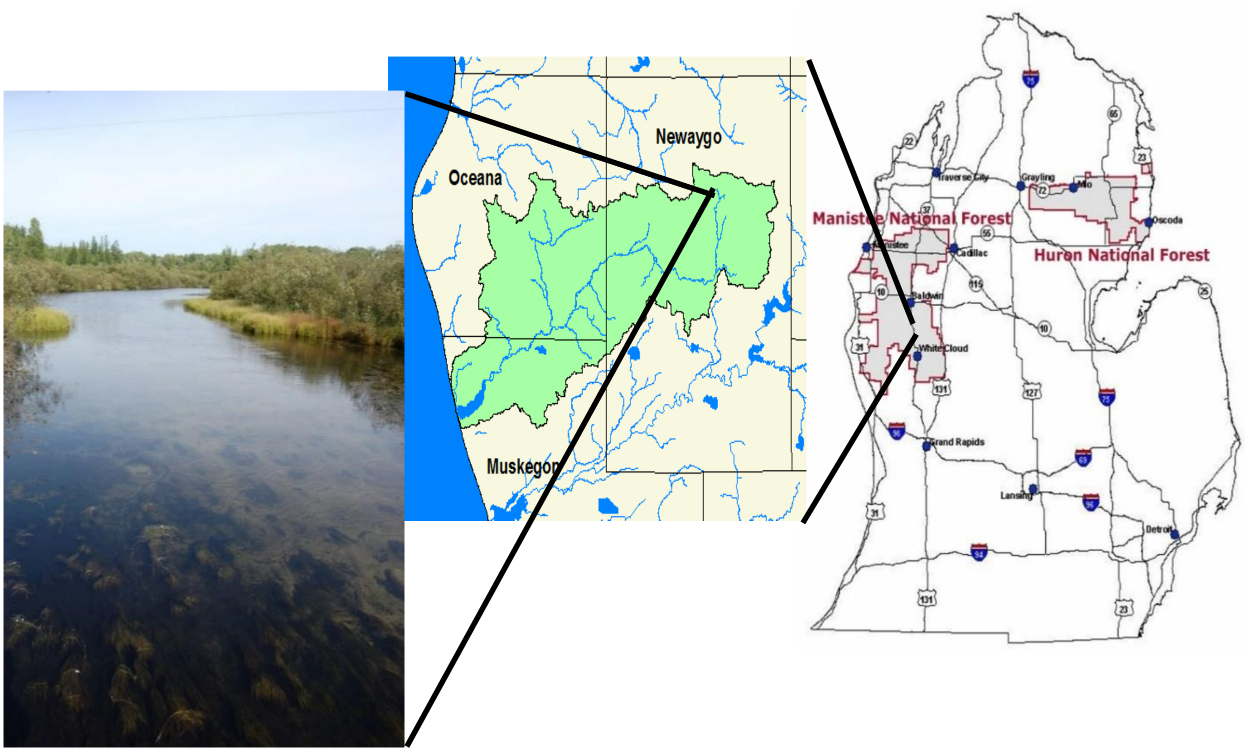

Figure 1: Map of Michigan showing the location of Manistee National Forest (right), map of the White River watershed (middle) and a picture of the headwaters from the 6 Mile Road bridge (left). (Maps are U.S. Forest Service maps)

The river was designated "Scenic" by the state of Michigan, and is an important trout habitat (Doss, 2009). This study took place specifically at the headwaters of the White, where groundwater springs dot the streambed and some small creeks trickle into the river from the surrounding wetlands. These springs are of particular interest because of their amounts of groundwater discharge as well as their spatial distribution. Approximately 13 of these springs are located in one particular area of the streambed approximately 100 m^2 in area. These springs have diameters in the tens of centimeters, and are discharging enough groundwater to be visibly apparent. The reason behind the

restricted geographic distribution of the springs is unclear, and remains one of the principal questions relating to the system.

The groundwater discharging into the headwaters of the stream is part of a confined aquifer system. A sandy recharge area of the aquifer lies just west of the stream; moving towards the stream the aquifer becomes overlain by a peat bog with interbedded marl that acts as a confining layer (Ellis and Doss, 2011) (Figure 2). The sand in this region is a fine-medium grained, homogeneous sandy glacial outwash. The aquifer then discharges into the White River, which is at the eastern edge of the wetland.

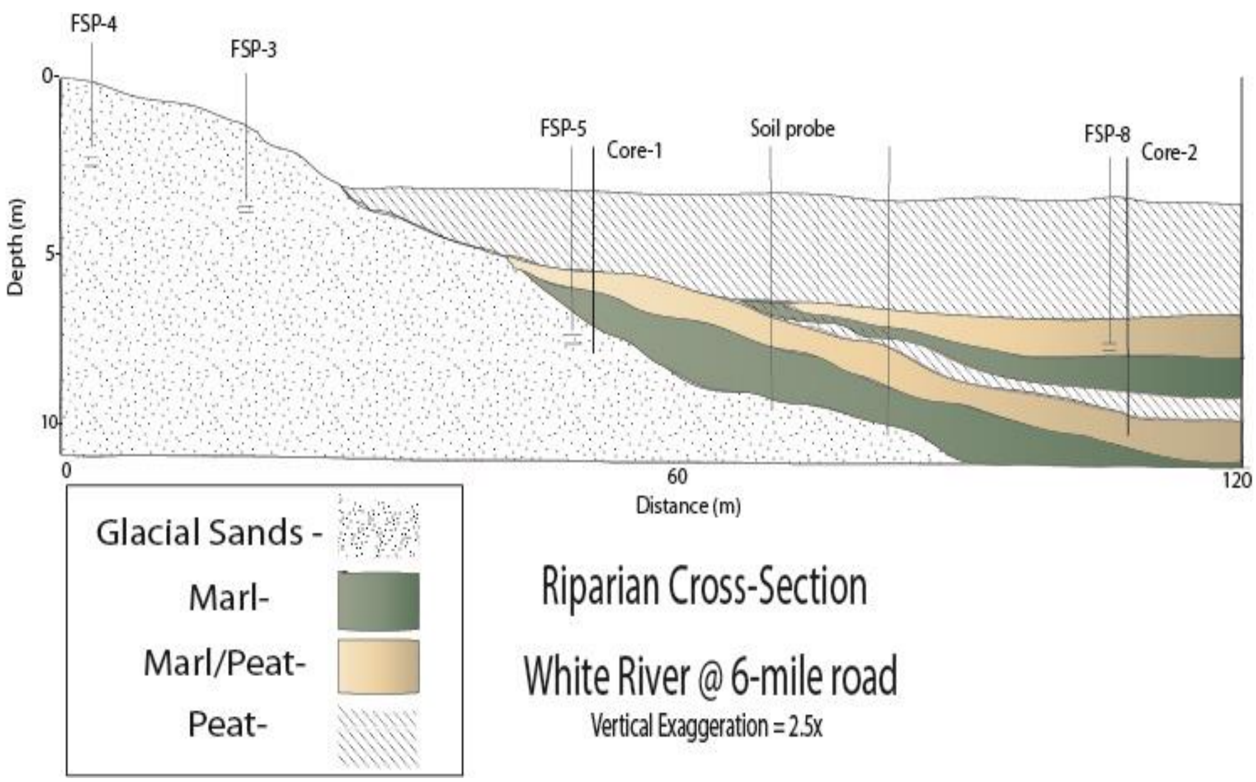

Figure 2: East – West cross section of the sandy recharge area in the upland and the wetland that confines the aquifer. The White River is to the east (right). Cores used in cross section development are labeled. Piezometers are labeled “FSP” for “Forest Service Piezometer.” (From Ellis and Doss, 2011)

Previous research in the area focused on several different aspects of groundwater-surface water interaction in the headwaters. Initial studies focused on installation of a piezometer network in the recharge area and riparian wetland to better understand temporal trends of groundwater and potential human impacts on groundwater discharge (Doss, 2009; Doss, et al., 2010). Collection of precipitation, stream stage and discharge measurements took place over the course of several years (Doss, et al., 2010). Stratigraphy of the wetland was defined using core samples (Ellis and Doss, 2011). More recent research defined modes of groundwater discharge in the streambed as either diffuse discharge or as conduit-style discharge (or springs), and attempted to use thermal gradients to map groundwater-surface water interaction (Doss, et al., 2012; Heighton, et al., 2012).

Better understanding of the aquifer and the role it plays in sustaining stream flow is important to preserve the local ecosystem functions. Groundwater can provide nutrients and inorganic ions to the surface waters (Hayashi and Rosenberry, 2002). In the mixing zone between the two waters (the "hyporheic zone") different organisms use the dissolved organic matter for food if it's not readily available in the surface water (Brunke and Gonser, 1997). In addition to the nutrients present in the water, groundwater discharge provides some stability to the temperature of the stream. Groundwater at depth remains at a relatively stable temperature throughout the year, suppressing seasonal surface temperature fluctuations. Where this groundwater is discharged into surface water, it provides cool water in the summer months and relatively warm water in the winter months. This nutrient-rich, stable temperature water is incredibly important to trout and salmon, which rely on areas of groundwater discharge for spawning purposes

(Baxter and Hauer, 2000; Hayashi and Rosenberry, 2002; Zorn, et al., 2012). The White River is home to various trout populations that depend upon groundwater discharge (Doss, 2009). Therefore, it is relevant to better understand the role of groundwater in sustaining base flow.

The objective of this study was to better understand the role of the shallow groundwater in sustaining streamflow, and the relative importance of seasonal precipitation to aquifer recharge. Examining the isotopic ratios in the surface water and groundwater was the principal method used to gain a better understanding of the different parts of the system and the interaction between groundwater and surface water. By combining this knowledge with the quantified groundwater and stream discharges, the effects of changes to the aquifer on the stream are better understood. The effects of changes to precipitation patterns on groundwater recharge (and subsequently streamflow) can also be better understood. All of this is in an effort to help the U.S. Forest Service better manage this natural resource and better prepare for possible future changes to the system.

Materials and Methods

Water samples were collected from each of the seven piezometers, from the stream, from several of the springs, several non-spring sites in the streambed and from precipitation (Figure 3). Piezometer samples were collected using standard plastic bailers of various diameters. Groundwater from springs and non-spring sites was collected using a pushpoint sampler. Snow samples were collected by hand in the upland recharge area near FSP-2. Rain samples were collected from the nearest U.S. Forest Service office in Baldwin (approximately 32 kilometers north of the headwaters). Samples were put into

15 mL centrifuge vials which were filled as completely as possible to prevent any evaporation within the vial. Samples were stored at room temperature until analyzed in the lab. Isotopic sampling took place from February 2015 to January 2016 with a sampling frequency ranging from once a week to once a month depending on the time of year.

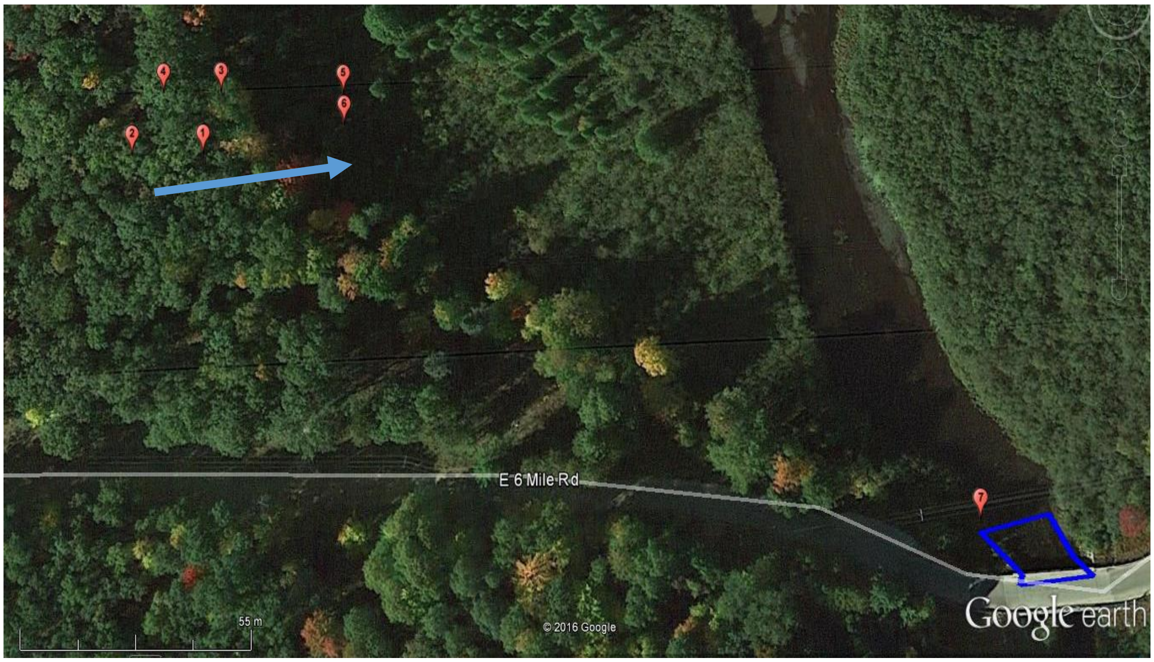

Figure 3: Aerial view of the study site. Piezometers are labeled by their number (without the "FSP" designation). The blue arrow indicates the approximate direction of groundwater flow. The blue box in the stream is the area where springs are present. Image from Google Earth.

The $\delta^{18}O$ and δD of the samples were measured using the Los Gatos Triple Water Isotope Analyzer in the Department of Geosciences at Western Michigan University. Both hydrogen and oxygen isotopes are reported relative to VSMOW.

The electrical conductivity of the samples was measured using a Myron L Company ULTRAPEN PT1. Typically electrical conductivity measurements are made in the field because if delayed, some of the ions in the water can precipitate (USGS, 1998).

Instead, the conductivities of the samples in this study were measured in the lab following isotopic analysis, looking at overall trends seen in the data rather than the individual sample measurements. Because the trends in the conductivity data correlate with those seen in the isotopic data, the conductivity measurements can still provide useful information on the relationships between the different waters.

During the summer of 2013, basic water quality measurements of both streambed groundwater and surface water were taken using a QW probe calibrated using standard field parameters. Because the head of the spring water was higher than the stream stage, when a piezometer was inserted in the spring it created an artesian well. After allowing the water to flow out of the well for a few minutes, the QW probe could be inserted into the well to collect temperature, pH and conductivity measurements of the spring water. The probe would then be inserted into the stream water adjacent to the spring to get a comparative surface water reading.

In addition to the different chemical parameters measured, certain physical hydrologic measurements were also made in the field. Groundwater head and stream stage were measured using a Solinst Model 101 water level meter. Stream stage was always measured at FSP-7. Stream discharge was measured on the downstream side of the 6 Mile Road bridge using a Marsh-McBirney, Inc. Model 2000 FLO-MATE portable electromagnetic flowmeter. Two seepage meters were constructed from plastic 55-gallon storage drums following the design of USGS scientist Don Rosenberry (Rosenberry, 2008). These seepage meters were deployed in both spring and diffuse discharge areas for intervals of minutes to days depending on the rate of groundwater discharge filling 2.5 L plastic collection bags. In an effort to investigate the difference between spring and non-

spring sites, sediment samples were collected from various points in the streambed and analyzed for hydraulic conductivity in the lab using a constant head permeameter. Sediment analysis and seepage meter measurements also took place during May and June of 2013.

Results

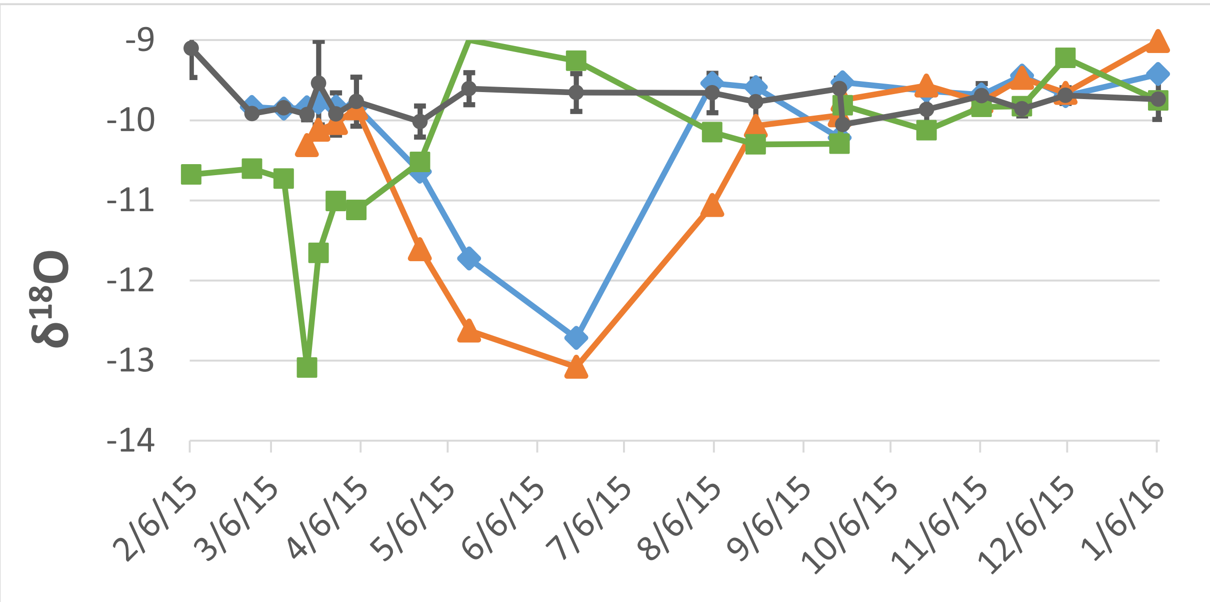

Figure 4: $\delta^{18}O$ of the stream water (green), the upland piezometers (FSP-1(blue) and FSP-2 (orange)), and the average $\delta^{18}O$ of the wetland piezometers, the streambed piezometer and the groundwater discharge (purple). Error bars of the groundwater average are the standard deviation for that date.

Results from isotope data

$\delta^{18}O$ in precipitation ranged from -25.7‰ to -6.4‰ (Table 1, Figure 4). $\delta^{18}O$ in groundwater samples ranged from -13.1‰ to -8.4‰ with a mean of -9.86‰. Stream $\delta^{18}O$ ranged from -13.1‰ to -9.0‰ with a mean of -10.4‰.

δD in precipitation ranged from -190.4‰ to -34.2‰ (Table 1). Groundwater δD ranged from -91.2‰ to -57.9‰ with a mean of -67.1‰. δD in the stream ranged from -90.3‰ to -60.7‰ with a mean of -68.8‰.

	All 259 Samples		All Groundwater n = 226		Stream Water n = 19		Snow n = 6		Rain n = 8	
	Mean (‰)	σ (‰)	Mean (‰)	σ (‰)	Mean (‰)	σ (‰)	Mean (‰)	σ (‰)	Mean (‰)	σ (‰)
$\delta^{18}O$	-10.41	2.43	-9.86	0.62	-10.37	0.92	-20.08	3.07	-10.62	3.82
δD	-70.93	18.31	-67.09	4.29	-70.03	6.60	-143.86	24.28	-70.21	30.80

Table 1: Mean and standard deviation (σ) of isotope data from all water samples

Electrical conductivity results

Groundwater had an average electrical conductivity of 303.6 µS/cm with a standard deviation of 48.7 (Figure 5). Stream water had a mean conductivity of 265.0 µS/cm with a standard deviation of 46.1. Precipitation's average conductivity was 24.7 µS/cm with a standard deviation of 16.4.

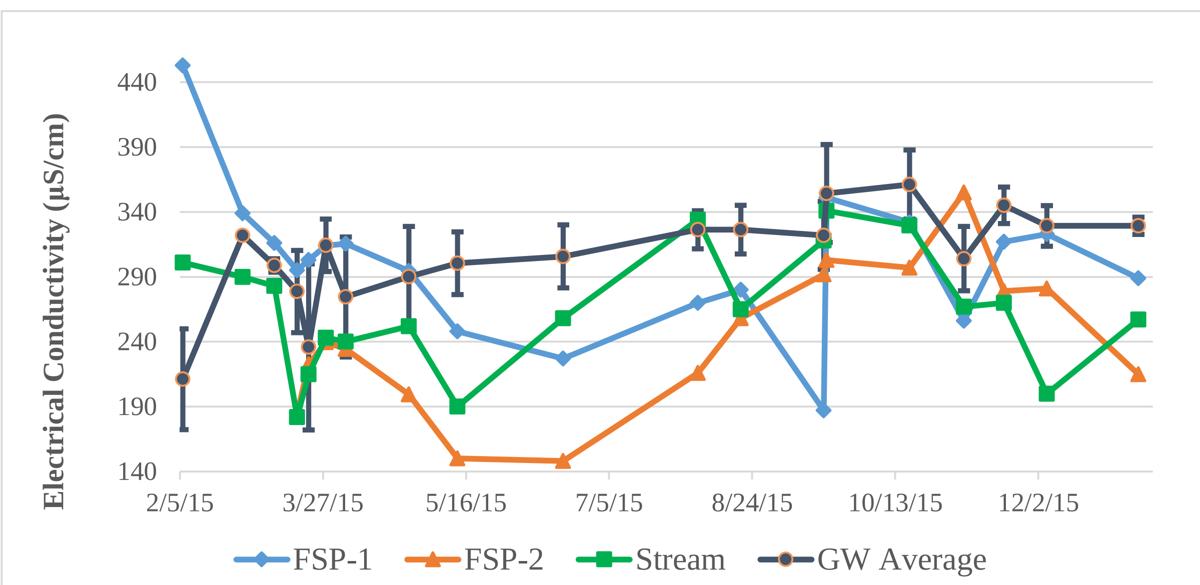

Figure 5: Electrical conductivity of the upland groundwater (FSP-1 and FSP-2), stream water, and average groundwater. Error bars are the standard deviation for that sampling period.

Water quality

Two noteworthy comparisons occur between the chemical data from 2013 and 2015-16. First, the springs have electrical conductivity values that are in a similar range to those measured several years apart. The average spring conductivity in 2013 was 334.9 μS/cm with a standard deviation of 8.95. The average conductivity of springs in 2015-16 was 313.1 μS/cm. The second comparison is the springs showed chemical signatures that were distinct from the surface water. This is true for the water quality measurements in 2013 as well as the isotopic data from 2015-16. The average temperature across the springs for 2013 was 9.12^{0}C with a standard deviation of 0.25; the average surface water temperature was 14.68^{0}C with a standard deviation of 1.76. The average δ^{18}O of the springs was -9.86‰ with a standard deviation of 0.18 and the average δD was -67.6‰ with a standard deviation of 0.40. Average δ^{18}O of the springs was very similar to that of the stream, with a difference of 1.1‰ or less, and most of the time the difference was less only 0.5‰. The springs were almost always more enriched than the stream.

Physical hydrology

Groundwater head in the upland recharge area averaged 275.60 meters above sea level and fluctuated approximately 0.10 m or less during the year. The differences in head between the four piezometers in the upland suggest a general groundwater flow direction of east northeast (Figure 3). The piezometers in the wetland had an average groundwater head of 274.54 meters above sea level, with fluctuations typically 0.12 m or less. The wetland groundwater levels indicated upward flow of the groundwater, with the water in FSP-5 (the piezometer in the aquifer beneath the wetland) always higher than the water in FSP-6 (the well screened in the peat). Stream stage averaged 273.41 meters above sea

level. Again, there is indication of upward flow of groundwater by streambed groundwater head. Water levels in FSP-7 were always 0.02-0.05 m higher than the stream stage. That fact combined with the presence of the springs confirms this section of the White River is a gaining stream.

Groundwater discharge amounts greatly depended on the location in the streambed. The springs had an average discharge of $7.3*10^{-3}$ cm/s while the diffuse discharge measurements ranged from $1.7*10^{-7}$ cm/s to $1.4*10^{-4}$ cm/s (Figures 6 and 7). Only four of the springs were measured due to the aquatic riparian vegetation at the time restricting seepage meter use to the center of the streambed. Diffuse discharge measurements included areas in close proximity to springs as well as areas upstream from where the springs occur. Spring discharge amounts showed much less variability both spatially and temporally than diffuse discharge amounts.

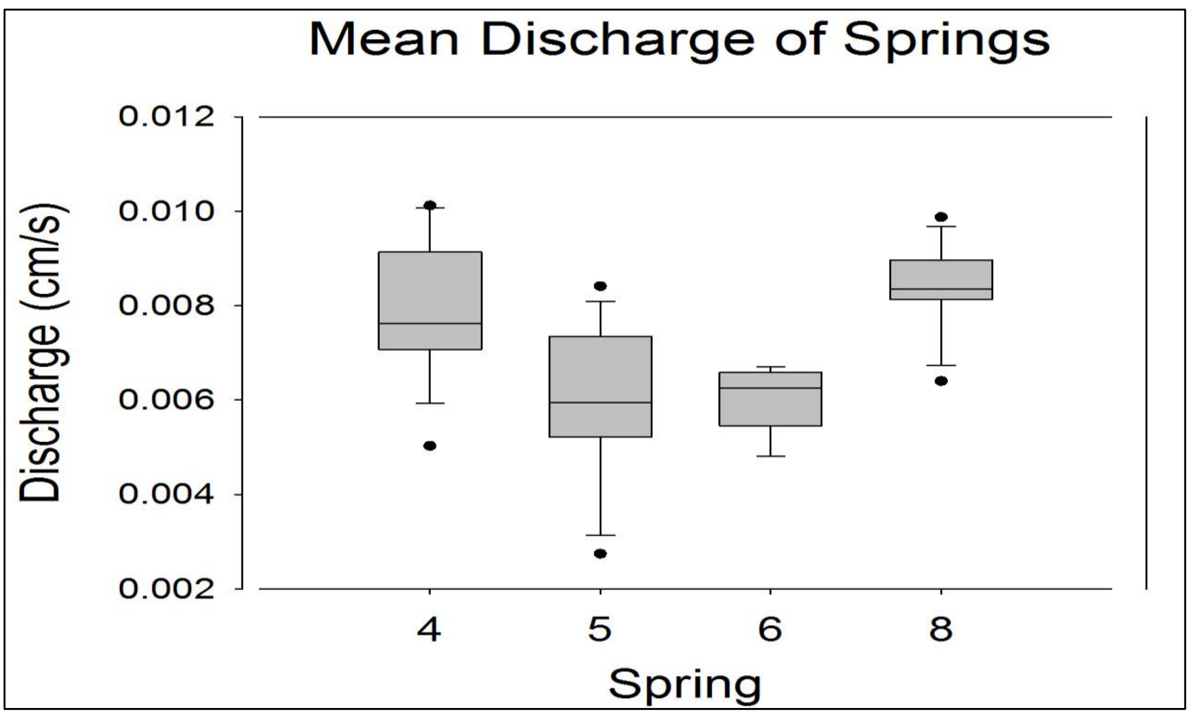

Figure 6: Box-and-whisker plot of the mean spring discharge for four individual springs during May-June 2013.

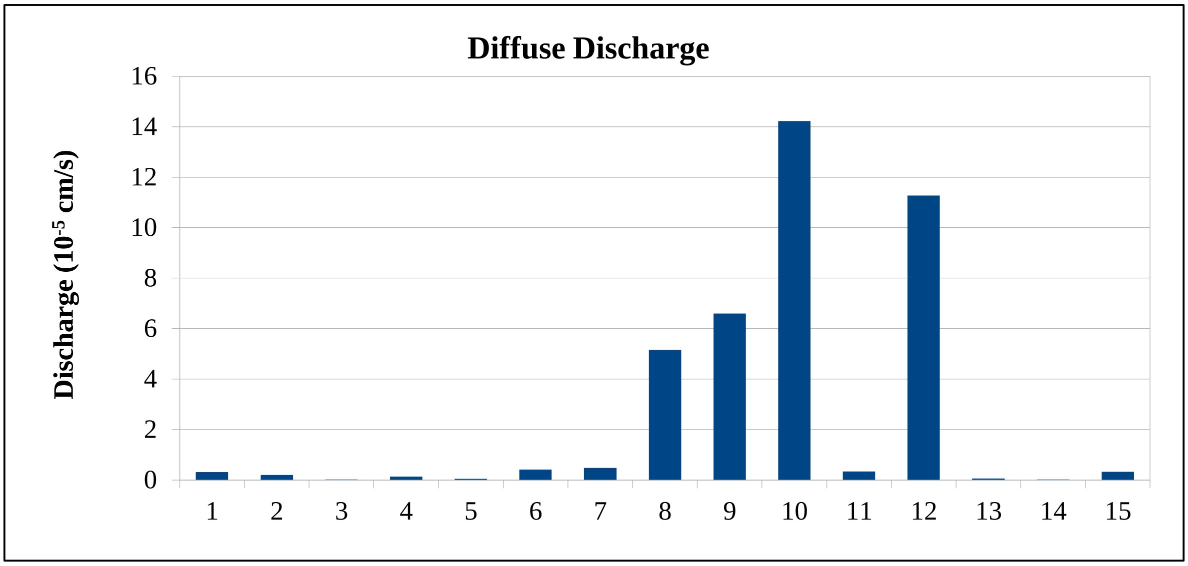

Figure 7: Diffuse discharge amounts from May-June 2013. Numbers on the x-axis indicate individual locations in the streambed.

Sediment analysis did little to distinguish spring and non-spring sites. Both sediment sources were composed primarily of well-sorted, medium-grained quartz sand. The spring sites were slightly better sorted, and had less organics and clays than the diffuse discharge areas. However, both spring and non-spring sites had laboratory hydraulic conductivity values of 10^{-2} cm/s.

Discharge of the stream during 2015 ranged from 0.36 m^3/s to 1.53 m^3/s, with an average discharge of 0.67 m^3/s. Because discharge measurements were only taken on a weekly to monthly basis rather than daily, the discharge of the stream fluctuated much more than this study's data indicate. However, for the purposes of this research the trends in stream discharge are still noteworthy when compared with the $\delta^{18}O$ of the stream water, as will be shown later.

Discussion

Precipitation

Precipitation samples had isotopic values in the expected range. Previous studies in Kalamazoo (approximately 165 km south of the White River) have found $\delta^{18}O$ in precipitation to range from -15.46‰ to -5.73‰ and δD ranged from -100‰ to -30.4‰ (Machavaram and Krishnamurthy, 1994). Precipitation in this study is likely more depleted because sampling in this study took place slightly further from the precipitation source (the Gulf of Mexico), causing more depletion from the rain out effect (Clark and Fritz, 1997). Snow samples were the most depleted, with an average $\delta^{18}O$ of -20.08‰. The snow is most depleted in February before the snow melt begins, and it becomes more enriched as the melt progresses and the lighter isotopes are incorporated into the liquid phase, leaving the heavier isotopes in the leftover snow. Rain samples showed much more variation in their isotopic composition, and became generally more depleted as the seasons transitioned from fall to winter and precipitation became colder. All of the precipitation samples create a meteoric water line with a slope of 7.54 and a deuterium-excess of 8.0 (Figure 8). The slope is similar to the slope of 7.5-7.75 found by Machavaram and Krishnamurthy (1994) in Kalamazoo. The deuterium excess (d-excess, the y-intercept) is much lower than that reported by Machavaram and Krishnamurthy (15.6-23.7‰). The higher d-excess in that study was attributed to the influence of evaporation from Lake Michigan. The difference may indicate that the White River watershed does not receive as much "Lake Effect" precipitation as Kalamazoo, but since precipitation samples were only collected during the fall and winter months, a more

frequent sampling interval may cause the LMWL to become more similar to that of precipitation in southwest Michigan.

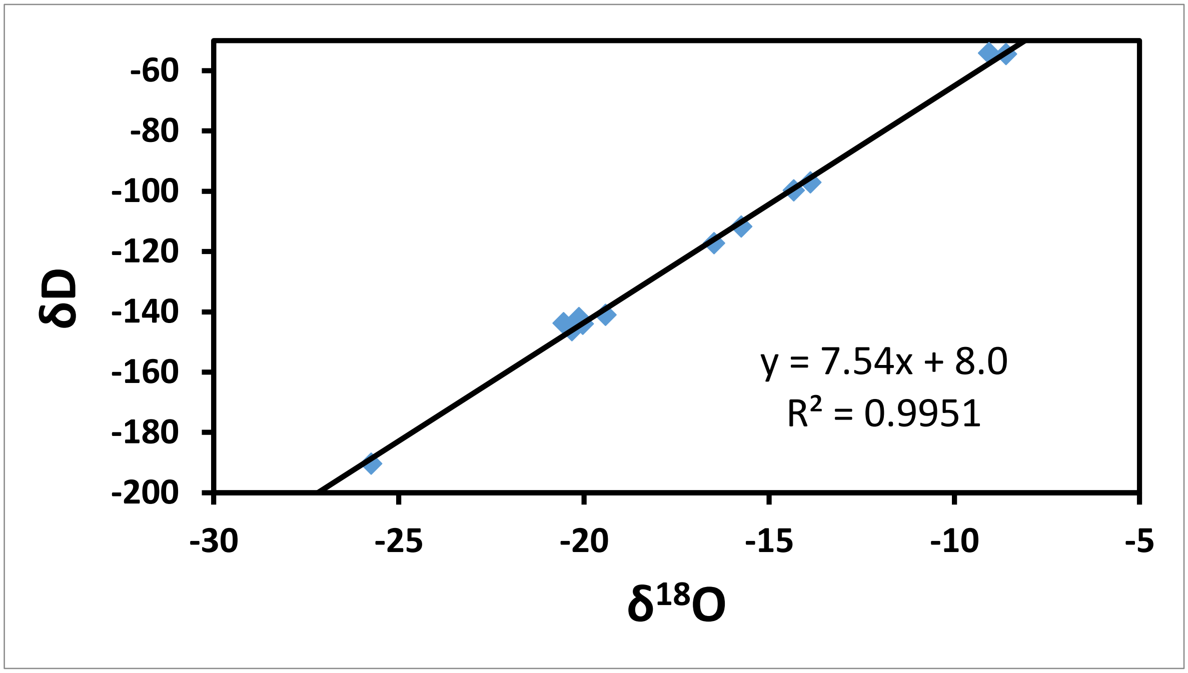

Figure 8: Local meteoric water line developed from collected precipitation samples.

Relative contributions of precipitation to aquifer recharge and of groundwater discharge to streamflow were assessed using a simple mixing model. For example, the $\delta^{18}O$ mixing equation for groundwater contribution to streamflow would be:

$$\boldsymbol{\delta^{18}O_{S} = x(\delta^{18}O_{GW}) + (1 - x)(\delta^{18}O_{P})} \qquad (1)$$

Where $\delta^{18}O_S$ is the $\delta^{18}O$ in the stream, $\delta^{18}O_{GW}$ is the isotopic composition of the groundwater, $\delta^{18}O_P$ is the oxygen isotopes in the precipitation (which is the main component of runoff contributing to the streamflow) and x is the relative contribution to streamflow by the groundwater.

Based on the isotopic composition of the aquifer over the course of the year the majority of recharge occurs in the form of rain, either from summer rains that are heavy enough to make it past the vegetation or from fall precipitation events that occur after this vegetation has died off. The seasonal contribution to recharge cannot be determined without more frequent precipitation sampling. The average $\delta^{18}O$ of the aquifer over the sampling period (-9.88‰) is much closer to the average rain $\delta^{18}O$ (-10.99‰) than the average snow $\delta^{18}O$ (-21.04‰). The average $\delta^{18}O$ of the rain in this study is more depleted than that of the groundwater because all of the rain samples were collected between September and December when it was cooler, which causes more depleted values in precipitation (Clark and Fritz, 1997). If rain samples had been collected during the warmer months it's likely the isotopic values in the rain would be more enriched and the average $\delta^{18}O$ would also increase. If $\delta^{18}O$ values in rain that are more depleted than the average $\delta^{18}O$ of the groundwater are excluded, then the average $\delta^{18}O$ of the rain becomes -7.94‰. Using this value the amount of recharge to the aquifer occurring as rain using the mixing model is calculated to be 85%. Possible errors in this approach can result mainly from the assumption that these isotopic values represent the actual average isotopic composition of the different waters. All averages could be more accurate with more frequent sampling. The precipitation values in particular could be improved because of the small sample set and the complex nature of isotopic fractionation during rainfall and snow melt (in other words, the isotopic values from the same precipitation can possibly change during the storm/melt (Fetter, 2001)).

Despite this estimated contribution the potential influence of snow melt on the aquifer is not to be ignored. The aquifer clearly shows depletion of isotopic ratios in the

upland during the late spring-early summer months when the melt water is able to percolate down to the water table (Figure 4). The upland wells are most depleted in late June, and then begin to return to their normal levels. By the time the groundwater reaches the wetland the melt water has thoroughly mixed with the preexisting groundwater, causing no significant depletion in isotopic levels in the wetland piezometers or in the streambed groundwater. For the rest of the sampling period all of the groundwater wells show similar isotopic compositions. Electrical conductivity measurements show similar trends, with the upland groundwater having lower conductivities at the same time that isotope values become more depleted because of the interaction with the melt water. Several temporal trends in the electrical conductivity data correlate with trends seen in the isotopic data that result from precipitation's influence (Figure 5). The conductivity of the stream water is lowest when the stream's isotopic composition is most depleted, further indicating a higher runoff contribution to stream flow on March 18.

If the depletion in the upland groundwater is in fact from the snowmelt, the recharge time is very delayed for a homogenous sand, especially when compared to the short response time seen in the groundwater to a rain event in September. Therefore, the changes seen in the groundwater may be due to rain influence, but without summer precipitation data it's unclear which interpretation from the isotope data is correct.

With a more frequent sampling interval there may be more fluctuations seen in the upland area due to rainfall events, but one set of samples was collected immediately before and after a rain event. This event occurs in late September, when the isotopic ratios become more enriched in the aquifer and the stream due to the addition of the enriched rain water. During this period samples were collected and water levels measured

just before a storm, and then just after. The storm produced 1.8 cm of rain, and all groundwater wells showed an increase in head ranging from 2 cm to 11 cm, with FSP-5 showing the largest increase. Stream stage increased by 6 cm, and discharge increased by 0.13 m^3/s. Following the rain the isotopic composition of the wells in the upland and of the stream became more enriched, as expected with the enriched rain added to the system. However, the wetland and streambed groundwater isotopic composition became more depleted, rather than more enriched as expected with the enriched rain entering the system. This suggests that precipitation contributes indirectly to streamflow by forcing the preexisting groundwater out of the aquifer and into the stream as it infiltrates the subsurface. While the isotopic composition of the upland groundwater becomes more enriched following the rain, it also becomes more conductive instead of less with the low-conductivity rain added. This may be the result of groundwater that had been trapped in the vadose zone since the previous precipitation event being "flushed" down to the water table with the subsequent precipitation event. If the water had been in the unsaturated zone for an extended period it may have raised the conductivity of that water while also enriching its isotopic composition through evaporative processes. Evaporation (and therefore isotopic enrichment) of groundwater in the unsaturated zone as well as from the water table has been shown to cause isotopic gradients within shallow groundwater (Barnes and Allison, 1988). Without knowledge of the soil saturation prior to the rain event or soil water samples this hypothesis cannot be confirmed.

Groundwater flow

Isotopic data from the aquifer, in conjunction with the groundwater head data and electrical conductivity measurements, provide insight into the flow path of the

groundwater and the dynamics of each aquifer section. Isotopic and conductivity data from the piezometers in the upland recharge area fluctuate the most over the study period as a result of precipitation's influence (Figures 4 and 5). Moving in the direction of flow as indicated by the groundwater elevations, the chemistry in the piezometers beneath and in the peat bog indicate the groundwater is thoroughly mixed by the time it reaches the wetland. The variations in the isotopic and conductivity data in these wells are more subdued than in the upland, with very minor changes during the year. Even major precipitation inputs during the spring snowmelt showed little effect on the wetland wells. The groundwater from the springs and diffuse discharge sites also fluctuated very little chemically, and were similar to those in the wetland, suggesting the groundwater discharging in the streambed is the well-mixed aquifer water. The streambed piezometer showed more variation. The data from FSP-7 are similar to that of the stream, indicating the water in this well has some stream water mixed in. The proximity of the piezometer to the bank of the stream may be the cause of this surface water influence, with stream water, hyporheic water, or precipitation mixing in with the riparian groundwater.

Throughout the sampling period groundwater other than FSP-1 and FSP-2, had similar isotopic compositions without any major fluctuations. The mean $\delta^{18}O$ of all the groundwater samples was -9.88‰ with a standard deviation of 0.64‰. When measurements from the upland are excluded the mean $\delta^{18}O$ for the groundwater is -9.76‰ with a standard deviation of only 0.30‰. The piezometers with isotopic trends most similar to the stream are FSP-6 and FSP-7, suggesting there may be some significant influence of the groundwater in the peat on the stream and riparian groundwater.

Streamflow

As discussed in previous sections, the stream samples showed significant influence from precipitation, especially during the snow melt in March which caused the stream to become isotopically depleted. However, even during these periods of significant precipitation influence, the majority of streamflow was still baseflow. Using the isotopic mixing model the average contribution of groundwater to streamflow was 86%. During the month of March when the stream chemistry showed the most influence from snow melt the calculated baseflow contribution was still 82% (Figure 9). The temporal trends in stream $\delta^{18}O$ mimic those of stream discharge, with peaks in discharge corresponding to more enriched $\delta^{18}O$ values, indicating that even during times of high flow there are still significant contributions by baseflow. This is seen during the spring snow melt in March. When discharge is at its highest, stream $\delta^{18}O$ values are the most enriched. If surface runoff were a major contributing factor to streamflow during this

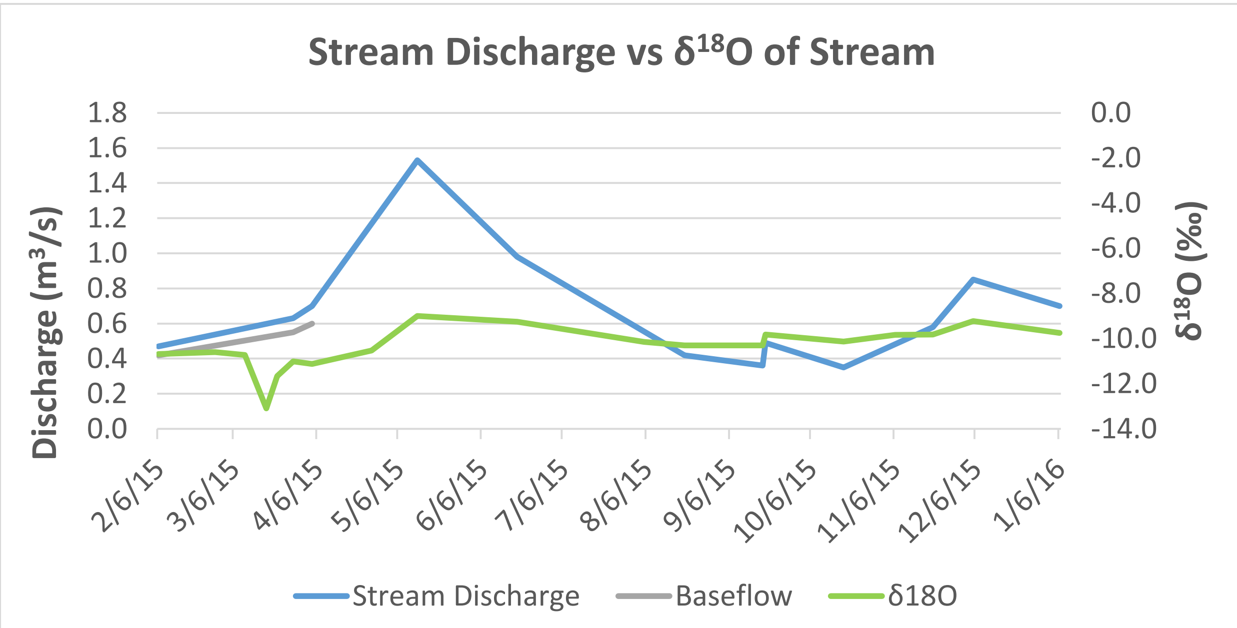

Figure 9: Hydrograph for the White River compared to the $\delta^{18}O$ of the stream, along with the baseflow during the spring snow melt.

time, the $\delta^{18}O$ values in the stream would drop as the depleted snow melt mixes with the stream water. Instead, the $\delta^{18}O$ rises in the stream, indicating that snowmelt is infiltrating the subsurface and displacing the more enriched groundwater out into the stream, rather than flowing across the land surface.

Unfortunately the isotope data do not elucidate the different sources of baseflow (i.e. springs and diffuse discharge). There was no significant statistical difference between the spring and diffuse isotopic data using a student's t-test analysis ($p=0.05$). Despite the large difference in discharge amounts between springs and diffuse discharge areas, the small number of springs present in the streambed limits the amount of contribution to flow. The significance of the spring discharge to streamflow most likely increases with lower streamflow amounts, but without temporal groundwater discharge data it's uncertain just how important these springs are to baseflow.

Study improvements

There are still many questions related to this system that remain unanswered, and several advances to methods used in this study could improve data accuracy and provide a better understanding of the system. Data on groundwater residence time, examining how long it takes the groundwater to move from the upland to the streambed, would provide a clearer understanding of flow and mixing rates in the aquifer. More frequent precipitation sampling would be informative about the seasonality of recharge and isotopic seasonality in precipitation. Finally, the different forms of groundwater discharge in the streambed should be further examined. The cause for the groundwater to discharge as both springs and diffuse discharge is most likely related to the geology of the

streambed and aquifer. Tracer experiments and groundwater mapping may provide a better perspective.

Conclusion

The isotopic composition of the groundwater, precipitation and stream water helped untangle the different components of the system. Recharge to the aquifer occurs primarily as rain in the summer or fall months, with only 15% of recharge estimated to occur as snow. Precipitation enters the groundwater system in the upland area, and then mixes with the pre-existing groundwater by the time it reaches the wetland. The interbedded peat and marl in the deeper layers of the wetland restrict the upward flow of the groundwater, promoting lateral flow and discharge into the streambed to the east as both diffuse discharge and springs. This groundwater discharge constitutes the majority of the overall streamflow, with an estimated 86% of the streamflow composed of baseflow.

Since current precipitation patterns may be disrupted in the future due to global climate change, this information could become more vital. Changes in precipitation could cause changes to groundwater recharge, which in turn could cause changes in the stream. This study may be useful in the future when these potential climate changes become better known by establishing a comparative baseline value for groundwater recharge and discharge.

CHAPTER III

SIGNIFICANCE OF THIS WORK

The objective of this study was to characterize the hydrology of the headwaters of the White River through stable isotopes of oxygen and hydrogen. This was accomplished by using the stable isotopes in precipitation, groundwater and stream water to estimate the contributions of snow and rain to groundwater recharge and the contribution of baseflow to overall stream flow.

These estimates are significant for two reasons. First, this study found that the majority of flow in the White River comes from groundwater, even during times of high surface runoff input. This is important because if changes occur to the groundwater system there will be impacts to the streamflow, which would affect the important ecosystems that rely on streamflow and groundwater discharge. Changes to the groundwater system most likely would result from either increased groundwater extraction in the area or changes to precipitation. While at the moment there are no efforts known to researchers to increase groundwater extraction from this aquifer, there may be potential changes to precipitation in the future due to global climate change. Thus the estimates of recharge in this study are significant because if the vast majority of recharge occurs as rain rather than snow, then lower snowfall amounts because of a warmer climate may not impact the groundwater system as severely as an overall decrease in yearly precipitation amounts. Both of these findings should help the United States Forest Service in managing the stream, and therefore the groundwater, going forward.

Appendix A

Complete isotope data

Appendix A

Complete isotope data

Sample Source	Date	δ^{18}O	δD
FSP-1	2/6/15	NaN	NaN
FSP-6	2/6/15	-9.4	-66.1
FSP-6	2/6/15	-9.5	-65.6
FSP-7	2/6/15	-8.4	-58.2
FSP-7	2/6/15	-9.0	-63.3
SNOW	2/6/15	-25.7	-190.4
STREAM	2/6/15	-10.7	-71.8
FSP-1	2/27/15	-9.9	-68.0
FSP-1	2/27/15	-9.8	-66.3
FSP-6	2/27/15	-10.0	-66.8
FSP-6	2/27/15	-9.9	-66.1
SNOW	2/27/15	-20.5	-143.7
STREAM	2/27/15	-10.6	-70.9
FSP-1	3/10/15	-9.9	-67.1
FSP-1	3/10/15	-9.8	-66.2
FSP-6	3/10/15	-9.9	-66.3
FSP-6	3/10/15	-9.9	-65.7
FSP-7	3/10/15	-9.7	-64.6
FSP-7	3/10/15	-9.9	-66.0
SNOW	3/10/15	-20.1	-142.1
STREAM	3/10/15	-10.7	-71.9
FSP-1	3/18/15	-9.8	-66.3
FSP-1	3/18/15	-9.9	-66.1
FSP-2	3/18/15	-10.4	-68.6
FSP-2	3/18/15	-10.3	-68.1
FSP-6	3/18/15	-9.9	-66.0
FSP-6	3/18/15	-9.9	-66.0
FSP-7	3/18/15	-9.9	-66.6
FSP-7	3/18/15	-10.0	-67.2
SNOW	3/18/15	-20.0	-144.0
STREAM	3/18/15	-13.1	-90.3
FSP-1	3/22/15	-9.8	-65.8
FSP-1	3/22/15	-9.8	-66.1
FSP-2	3/22/15	-10.2	-68.2
FSP-2	3/22/15	-10.0	-67.9

Appendix A – continued

Sample Source	**Date**	**$\delta^{18}O$**	**δD**
FSP-5	3/22/15	-8.6	-57.3
FSP-5	3/22/15	-9.0	-58.5
FSP-6	3/22/15	-9.9	-65.8
FSP-6	3/22/15	-9.9	-65.9
FSP-7	3/22/15	-9.9	-66.8
FSP-7	3/22/15	-10.0	-67.1
SNOW	3/22/15	-20.3	-146.1
STREAM	3/22/15	-11.7	-79.8
FSP-1	3/28/15	-9.8	-66.4
FSP-1	3/28/15	-9.9	-66.8
FSP-2	3/28/15	-10.1	-67.8
FSP-2	3/28/15	-10.0	-67.2
FSP-6	3/28/15	-9.6	-63.0
FSP-6	3/28/15	-9.6	-63.2
SNOW	3/28/15	-19.4	-141.0
STREAM	3/28/15	-11.0	-75.0
SPRING 4	3/28/15	-10.1	-68.7
SPRING 5	3/28/15	-9.8	-67.3
SPRING 8	3/28/15	-9.9	-67.0
SPRING 9	3/28/15	-9.8	-66.8
SPRING 12	3/28/15	-10.1	-67.8
D1	3/28/15	-10.3	-68.8
D2	3/28/15	-10.2	-67.8
FSP-1	4/4/15	-10.0	-66.6
FSP-1	4/4/15	-9.7	-66.3
FSP-2	4/4/15	-9.8	-67.1
FSP-2	4/4/15	-9.9	-67.4
FSP-5	4/4/15	-9.2	-61.8
FSP-5	4/4/15	-9.3	-63.1
FSP-6	4/4/15	-9.7	-65.4
FSP-6	4/4/15	-9.6	-65.8
FSP-7	4/4/15	-9.6	-64.6
FSP-7	4/4/15	-9.9	-67.4
STREAM	4/4/15	-11.1	-75.0
SPRING 4	4/4/15	-9.7	-66.1
SPRING 5	4/4/15	-10.2	-68.6
SPRING 8	4/4/15	-10.0	-67.8
SPRING 9	4/4/15	-10.0	-67.5

Appendix A – continued

Sample Source	**Date**	**$\delta^{18}O$**	**δD**
SPRING 12	4/4/15	-10.1	-67.7
D1	4/4/15	-10.1	-68.2
D2	4/4/15	-10.3	-67.5
FSP-1	4/26/15	-10.6	-69.9
FSP-1	4/26/15	-10.7	-70.1
FSP-2	4/26/15	-11.5	-75.8
FSP-2	4/26/15	-11.7	-77.8
FSP-5	4/26/15	-9.6	-62.5
FSP-5	4/26/15	-9.7	-63.0
FSP-6	4/26/15	-10.2	-67.4
FSP-6	4/26/15	-10.2	-67.9
FSP-7	4/26/15	-10.2	-67.6
FSP-7	4/26/15	-10.2	-67.9
STREAM	4/26/15	-10.5	-69.8
SPRING 1	4/26/15	-9.9	-67.0
SPRING 5	4/26/15	-10.4	-69.0
SPRING 8	4/26/15	-10.0	-67.4
SPRING 9	4/26/15	-10.2	-68.2
SPRING 12	4/26/15	-9.8	-66.8
D1	4/26/15	-10.0	-68.3
D2	4/26/15	-10.0	-67.0
FSP-1	5/13/15	-11.8	-80.7
FSP-1	5/13/15	-11.7	-79.7
FSP-2	5/13/15	-12.6	-86.0
FSP-2	5/13/15	-12.7	-86.0
FSP-5	5/13/15	-9.5	-62.5
FSP-5	5/13/15	-9.5	-61.8
FSP-6	5/13/15	-9.2	-64.5
FSP-6	5/13/15	-9.4	-65.3
FSP-7	5/13/15	-9.6	-66.4
FSP-7	5/13/15	-9.4	-66.2
STREAM	5/13/15	-9.0	-64.5
SPRING 4	5/13/15	-9.8	-67.3
SPRING 5	5/13/15	-9.8	-67.2
SPRING 8	5/13/15	-9.6	-66.1
SPRING 9	5/13/15	-9.9	-68.2
SPRING 13	5/13/15	-9.9	-67.4
D1	5/13/15	-9.8	-67.2

Appendix A – continued

Sample Source	**Date**	**$\delta^{18}O$**	**δD**
D2	5/13/15	-9.9	-66.4
FSP-1	6/19/15	-12.72	-88.20
FSP-2	6/19/15	-13.08	-91.17
FSP-5	6/19/15	-9.27	-61.98
FSP-6	6/19/15	-9.66	-65.57
FSP-7	6/19/15	-9.82	-66.50
SPRING 5	6/19/15	-10.12	-68.27
SPRING 8	6/19/15	-9.38	-65.27
SPRING 9	6/19/15	-10.03	-67.80
SPRING 13	6/19/15	-9.97	-68.09
D1	6/19/15	-9.75	-67.17
D2	6/19/15	-8.97	-63.87
STREAM	6/19/15	-9.26	-62.11
FSP-1	8/5/15	-9.54	-65.75
FSP-2	8/5/15	-11.06	-76.78
FSP-5	8/5/15	-9.37	-63.24
FSP-6	8/5/15	-9.64	-65.66
FSP-7	8/5/15	-9.97	-67.60
STREAM	8/5/15	-10.15	-68.03
FSP-1	8/20/15	-9.59	-65.95
FSP-2	8/20/15	-10.07	-69.67
FSP-5	8/20/15	-9.25	-64.88
FSP-6	8/20/15	-9.74	-66.80
FSP-7	8/20/15	-9.94	-67.53
SPRING 5	8/20/15	-10.03	-68.23
SPRING 8	8/20/15	-9.76	-66.97
SPRING 14	8/20/15	-9.76	-66.94
D1	8/20/15	-10.04	-68.79
D2	8/20/15	-10.11	-68.34
STREAM	8/20/15	-10.30	-68.76
STREAM	8/20/15	-10.29	-68.77
FSP-1	9/18/15	-9.70	-66.38
FSP-2	9/18/15	-9.66	-66.55
FSP-3	9/18/15	-10.46	-70.90
FSP-4	9/18/15	-10.82	-73.82
FSP-5	9/18/15	-9.85	-66.49
FSP-6	9/18/15	-9.91	-67.23
FSP-7	9/18/15	-9.00	-65.63

Appendix A – continued

Sample Source	**Date**	**$\delta^{18}O$**	**δD**
SPRING 5	9/18/15	-10.14	-69.09
SPRING 8	9/18/15	-10.24	-70.22
SPRING 13	9/18/15	-9.92	-68.11
D1	9/18/15	-8.38	-64.35
D2	9/18/15	-10.00	-67.83
STREAM	9/18/15	-10.34	-69.29
STREAM	9/18/15	-10.40	-69.31
RAIN	9/19/15	-7.70	-47.08
FSP-1	9/19/15	-9.87	-67.18
FSP-2	9/19/15	-9.90	-67.56
FSP-3	9/19/15	-10.20	-68.71
FSP-4	9/19/15	-9.95	-67.89
FSP-5	9/19/15	-10.05	-67.39
FSP-6	9/19/15	-10.55	-70.57
FSP-7	9/19/15	-10.76	-71.71
SPRING 5	9/19/15	-10.86	-72.60
SPRING 8	9/19/15	-10.58	-71.03
SPRING 9	9/19/15	-10.15	-68.64
SPRING 13	9/19/15	-8.81	-64.06
D1	9/19/15	-9.92	-66.73
D2	9/19/15	-9.90	-66.23
STREAM	9/19/15	-9.74	-63.62
STREAM	9/19/15	-9.68	-63.31
FSP-1	10/18/15	-9.63	-66.69
FSP-2	10/18/15	-9.57	-65.98
FSP-3	10/18/15	-9.71	-65.62
FSP-4	10/18/15	-9.39	-64.80
FSP-5	10/18/15	-9.96	-67.65
FSP-6	10/18/15	-9.58	-65.06
FSP-7	10/18/15	-10.04	-68.07
FSP-8	10/18/15	-9.73	-66.90
STREAM	10/18/15	-10.08	-66.82
STREAM	10/18/15	-10.18	-68.39
SPRING 1	10/18/15	-9.83	-67.49
SPRING 5	10/18/15	-10.07	-68.01
SPRING 8	10/18/15	-9.89	-68.49
SPRING 9	10/18/15	-10.04	-68.71
SPRING 13	10/18/15	-9.60	-65.26

Appendix A – continued

Sample Source	Date	δ¹⁸O	δD
D1	10/18/15	-10.21	-69.89
FSP-1	11/6/15	-9.68	-66.89
FSP-2	11/6/15	-9.77	-66.54
FSP-3	11/6/15	-9.83	-67.31
FSP-4	11/6/15	-9.43	-65.28
FSP-5	11/6/15	-9.68	-65.19
FSP-6	11/6/15	-9.76	-66.83
FSP-7	11/6/15	-9.46	-66.45
FSP-8	11/6/15	-9.49	-64.81
FSP-9	11/6/15	-9.56	-66.11
STREAM	11/6/15	-9.75	-65.90
STREAM	11/6/15	-9.92	-65.28
SPRING 5	11/6/15	-10.13	-69.24
SPRING 9	11/6/15	-10.08	-68.81
SPRING 13	11/6/15	-9.47	-65.03
SPRING 14	11/6/15	-9.83	-67.66
FSP-1	11/20/15	-9.44	-65.99
FSP-2	11/20/15	-9.47	-65.18
FSP-3	11/20/15	-9.81	-67.71
FSP-4	11/20/15	-9.49	-66.11
FSP-5	11/20/15	-9.76	-65.82
FSP-6	11/20/15	-9.78	-66.95
FSP-7	11/20/15	-9.94	-67.73
FSP-8	11/20/15	-9.48	-64.75
FSP-9	11/20/15	-9.54	-66.41
STREAM	11/20/15	-9.83	-65.37
SPRING 5	11/20/15	-9.98	-67.10
SPRING 9	11/20/15	-10.05	-68.92
SPRING 13	11/20/15	-9.81	-67.21
FSP-1	12/5/15	-9.70	-65.62
FSP-2	12/5/15	-9.66	-67.12
FSP-3	12/5/15	-8.97	-58.09
FSP-4	12/5/15	-9.35	-64.43
FSP-5	12/5/15	-9.73	-66.54
FSP-6	12/5/15	-9.69	-66.53
FSP-7	12/5/15	-9.80	-65.69
FSP-8	12/5/15	-9.74	-66.82
FSP-9	12/5/15	-9.71	-66.67

Appendix A – continued

Sample Source	**Date**	**$\delta^{18}O$**	**δD**
STREAM	12/5/15	-9.22	-60.66
SPRING 5	12/5/15	-9.70	-68.20
SPRING 8	12/5/15	-9.51	-67.74
SPRING 9	12/5/15	-9.53	-66.67
SPRING 13	12/5/15	-9.41	-67.32
FSP-1	1/6/16	-9.43	-67.16
FSP-2	1/6/16	-9.01	-62.90
FSP-3	1/6/16	-9.17	-65.67
FSP-4	1/6/16	-9.26	-63.51
FSP-6	1/6/16	-9.45	-65.06
FSP-7	1/6/16	-9.69	-67.39
FSP-8	1/6/16	-9.43	-65.22
STREAM	1/6/16	-9.75	-64.94
SPRING 4	1/6/16	-10.07	-68.95
SPRING 6	1/6/16	-10.01	-68.55
SPRING 8	1/6/16	-9.93	-67.28
SPRING 9	1/6/16	-10.14	-69.92
SPRING 13	1/6/16	-10.19	-69.54
SNOW	1/6/16	-14.34	-99.73
RAIN	10/8/15	-7.59	-48.78
RAIN	10/24/15	-6.36	-34.24
RAIN	10/27/15	-15.72	-110.66
RAIN	10/27/15	-15.79	-112.77
RAIN	10/31/15	-16.49	-117.18
RAIN	11/12/15	-9.00	-52.85
RAIN	11/12/15	-9.13	-55.46
RAIN	11/17/15	-8.60	-54.43
RAIN	12/1/15	-13.89	-97.03
FSP-1	9/18/15	-10.22	-68.28
FSP-2	9/18/15	-9.94	-64.92
FSP-3	9/18/15	-10.51	-68.56
FSP-4	9/18/15	-10.92	-74.50
FSP-5	9/18/15	-9.78	-65.11
FSP-6	9/18/15	-9.66	-65.66
FSP-7	9/18/15	-9.68	-66.45
SPRING 5	9/18/15	-9.54	-67.23
SPRING 8	9/18/15	-9.37	-66.45
SPRING 13	9/18/15	-9.39	-69.81

Appendix A – continued

Sample Source	**Date**	**$\delta^{18}O$**	**δD**
D1	9/18/15	-9.46	-67.50
D2	9/18/15	-9.49	-66.40
STREAM	9/18/15	-10.29	-70.71
RAIN	9/19/15	-7.20	-44.12
FSP-1	9/19/15	-9.53	-64.68
FSP-2	9/19/15	-9.75	-65.18
FSP-3	9/19/15	-9.86	-66.46
FSP-4	9/19/15	-9.93	-66.28
FSP-5	9/19/15	-10.38	-70.11
FSP-6	9/19/15	-10.01	-66.58
FSP-7	9/19/15	-10.20	-67.29
SPRING 5	9/19/15	-10.42	-70.83
SPRING 8	9/19/15	-9.97	-67.41
SPRING 9	9/19/15	-9.95	-67.05
SPRING 13	9/19/15	-9.50	-64.51
D1	9/19/15	-9.79	-67.15
D2	9/19/15	-9.68	-66.09
STREAM	9/19/15	-9.81	-67.87

Appendix B

Complete electrical conductivity data

Appendix B

Complete electrical conductivity data

Sample Source	Date	EC (µS/cm)
FSP-1	2/6/15	453.0
FSP-6	2/6/15	250.0
FSP-7	2/6/15	172.3
SNOW	2/6/15	301.0
STREAM	2/6/15	15.1
FSP-1	2/27/15	339.0
FSP-6	2/27/15	322.0
SNOW	2/27/15	290.0
STREAM	2/27/15	35.6
FSP-1	3/10/15	316.0
FSP-6	3/10/15	304.0
FSP-7	3/10/15	293.5
SNOW	3/10/15	68.1
STREAM	3/10/15	283.0
FSP-1	3/18/15	295.0
FSP-2	3/18/15	184.5
FSP-6	3/18/15	247.0
FSP-7	3/18/15	310.5
SNOW	3/18/15	31.4
STREAM	3/18/15	182.0
FSP-1	3/22/15	303.0
FSP-2	3/22/15	222.5
FSP-5	3/22/15	149.5
FSP-6	3/22/15	256.5
FSP-7	3/22/15	302.0
SNOW	3/22/15	7.5
STREAM	3/22/15	215.0
FSP-1	3/28/15	314.0
FSP-2	3/28/15	239.5
FSP-6	3/28/15	313.5
SNOW	3/28/15	13.2
STREAM	3/28/15	243.0
SPRING 4	3/28/15	324.0
SPRING 5	3/28/15	332.0
SPRING 8	3/28/15	265.0

Appendix B – continued

Sample Source	Date	EC (µS/cm)
SPRING 9	3/28/15	262.0
SPRING 12	3/28/15	241.0
D1	3/28/15	319.0
D2	3/28/15	360.0
FSP-1	4/4/15	315.5
FSP-2	4/4/15	234.5
FSP-5	4/4/15	187.0
FSP-6	4/4/15	315.0
FSP-7	4/4/15	273.0
STREAM	4/4/15	240.0
SPRING 4	4/4/15	310.0
SPRING 5	4/4/15	328.0
SPRING 8	4/4/15	302.0
SPRING 9	4/4/15	320.0
SPRING 12	4/4/15	286.0
D1	4/4/15	278.0
D2	4/4/15	299.0
FSP-1	4/26/15	294.5
FSP-2	4/26/15	199.5
FSP-5	4/26/15	220.0
FSP-6	4/26/15	305.5
FSP-7	4/26/15	334.5
STREAM	4/26/15	252.0
SPRING 1	4/26/15	314.0
SPRING 5	4/26/15	333.0
SPRING 8	4/26/15	307.0
SPRING 9	4/26/15	326.0
SPRING 12	4/26/15	259.0
D1	4/26/15	271.0
D2	4/26/15	294.0
FSP-1	5/13/15	248.0
FSP-2	5/13/15	150.0
FSP-5	5/13/15	259.5
FSP-6	5/13/15	315.5
FSP-7	5/13/15	332.0
STREAM	5/13/15	190.0
SPRING 4	5/13/15	296.0
SPRING 5	5/13/15	326.0

Appendix B – continued

Sample Source	**Date**	**EC (µS/cm)**
SPRING 8	5/13/15	314.0
SPRING 9	5/13/15	256.0
SPRING 13	5/13/15	302.0
D1	5/13/15	291.0
D2	5/13/15	303.0
FSP-1	6/19/15	227.0
FSP-2	6/19/15	148.0
FSP-5	6/19/15	266.0
FSP-6	6/19/15	325.0
FSP-7	6/19/15	332.0
SPRING 5	6/19/15	326.0
SPRING 8	6/19/15	262.0
SPRING 9	6/19/15	294.0
SPRING 13	6/19/15	281.0
D1	6/19/15	321.0
D2	6/19/15	309.0
STREAM	6/19/15	258.0
FSP-1	8/5/15	270.0
FSP-2	8/5/15	216.0
FSP-5	8/5/15	309.0
FSP-6	8/5/15	325.0
FSP-7	8/5/15	345.0
STREAM	8/5/15	334.0
FSP-1	8/20/15	280.0
FSP-2	8/20/15	258.0
FSP-5	8/20/15	309.0
FSP-6	8/20/15	329.0
FSP-7	8/20/15	361.0
SPRING 5	8/20/15	334.0
SPRING 8	8/20/15	278.0
SPRING 14	8/20/15	322.0
D1	8/20/15	295.0
D2	8/20/15	349.0
STREAM	8/20/15	265.0
FSP-1	9/18/15	187.0
FSP-2	9/18/15	292.0
FSP-3	9/18/15	276.0
FSP-4	9/18/15	175.0

Appendix B – continued

Sample Source	Date	EC (µS/cm)
FSP-5	9/18/15	338.0
FSP-6	9/18/15	328.0
FSP-7	9/18/15	358.0
SPRING 5	9/18/15	324.0
SPRING 8	9/18/15	280.0
SPRING 13	9/18/15	252.0
D1	9/18/15	294.0
D2	9/18/15	307.0
STREAM	9/18/15	318.0
RAIN	9/19/15	20.2
FSP-1	9/19/15	351.0
FSP-2	9/19/15	303.0
FSP-3	9/19/15	377.0
FSP-4	9/19/15	334.0
FSP-5	9/19/15	378.0
FSP-6	9/19/15	306.0
FSP-7	9/19/15	413.0
SPRING 5	9/19/15	327.0
SPRING 8	9/19/15	342.0
SPRING 9	9/19/15	370.0
SPRING 13	9/19/15	349.0
D1	9/19/15	348.0
D2	9/19/15	307.0
STREAM	9/19/15	341.0
FSP-1	10/18/15	332.0
FSP-2	10/18/15	297.0
FSP-3	10/18/15	294.0
FSP-4	10/18/15	332.0
FSP-5	10/18/15	360.0
FSP-6	10/18/15	349.0
FSP-7	10/18/15	404.0
FSP-8	10/18/15	361.0
STREAM	10/18/15	329.5
SPRING 1	10/18/15	350.0
SPRING 5	10/18/15	341.0
SPRING 8	10/18/15	257.0
SPRING 9	10/18/15	340.0
SPRING 13	10/18/15	372.0

Appendix B – continued

Sample Source	**Date**	**EC (µS/cm)**
D1	10/18/15	350.0
FSP-1	11/6/15	256.0
FSP-2	11/6/15	355.0
FSP-3	11/6/15	350.0
FSP-4	11/6/15	329.0
FSP-5	11/6/15	339.0
FSP-6	11/6/15	286.0
FSP-7	11/6/15	276.0
FSP-8	11/6/15	331.0
FSP-9	11/6/15	318.0
STREAM	11/6/15	267.0
SPRING 5	11/6/15	333.0
SPRING 9	11/6/15	313.0
SPRING 13	11/6/15	350.0
SPRING 14	11/6/15	265.0
FSP-1	11/20/15	317.0
FSP-2	11/20/15	279.0
FSP-3	11/20/15	350.0
FSP-4	11/20/15	281.0
FSP-5	11/20/15	351.0
FSP-6	11/20/15	337.0
FSP-7	11/20/15	365.0
FSP-8	11/20/15	355.0
FSP-9	11/20/15	347.0
STREAM	11/20/15	270.0
SPRING 5	11/20/15	344.0
SPRING 9	11/20/15	306.0
SPRING 13	11/20/15	334.0
FSP-1	12/5/15	323.0
FSP-2	12/5/15	281.0
FSP-3	12/5/15	266.0
FSP-4	12/5/15	330.0
FSP-5	12/5/15	342.0
FSP-6	12/5/15	344.0
FSP-7	12/5/15	305.0
FSP-8	12/5/15	339.0
FSP-9	12/5/15	333.0
STREAM	12/5/15	200.00

Appendix B – continued

Sample Source	**Date**	**EC (μS/cm)**
SPRING 5	12/5/15	335.0
SPRING 8	12/5/15	330.0
SPRING 9	12/5/15	312.0
SPRING 13	12/5/15	327.0
FSP-1	1/6/16	289.0
FSP-2	1/6/16	215.0
FSP-3	1/6/16	325.0
FSP-4	1/6/16	287.0
FSP-6	1/6/16	335.0
FSP-7	1/6/16	320.0
FSP-8	1/6/16	375.0
STREAM	1/6/16	257.0
SPRING 4	1/6/16	342.0
SPRING 6	1/6/16	325.0
SPRING 8	1/6/16	339.0
SPRING 9	1/6/16	306.0
SPRING 13	1/6/16	354.0
SNOW	1/6/16	57.7
RAIN	10/8/15	38.5
RAIN	10/24/15	42.9
RAIN	10/27/15	22.6
RAIN	10/31/15	18.5
RAIN	11/12/15	9.4
RAIN	11/17/15	13.1
RAIN	12/1/15	9.4

Appendix C

Complete water quality data

Appendix C

Complete water quality data

Groundwater					Stream Water				
Date	Spring	Temperature (^0C)	Electrical Conductivity (µs/cm)	pH	Date	Spring Associated	Temperature (^0C)	Electrical Conductivity (µs/cm)	pH
05/16/13	1	8.86	330.0	6.48	05/16/13	1	14.05	283.0	6.53
	3	9.02	344.0	6.87		3			
	4	9.29	329.0	6.98		4	13.35	275.0	7.02
	5	9.06	333.0	6		5	16.62	277.0	6.08
05/17/13	6	9.15	300.0	7.32	05/17/13	6	12.18	280.0	6.91
	7	9.56	332.0	6.73		7	12.28	280.0	6.62
	8	8.95	334.0	6.51		8	12.38	281.0	6.65
	9	8.98	344.0	6.42		9	12.36	280.0	6.44
	10	9.78	344.0	6.36		10	12.36	280.0	6.25
06/03/13	3	8.68	344.0	6.67	06/03/13	3	14.51	264.0	6.71
	4	9.14	330.0	6.63		4	13.76	243.0	6.6
	5	9.16	332.0	6.79		5	14.04	242.0	6.61
	6	9.62	332.0	6.72		6	14.1	243.0	6.54
	7	9.3	333.0	6.6		7	14.79	244.0	6.43
	8	9.33	332.0	6.42		8	14.57	245.0	6.38
	9	9.06	340.0	6.42		9	14.71	246.0	6.33
	10	9.07	339.0	6.36		10	14.88	245.0	6.37
06/18/13	1	8.85	334.0	5.4	06/18/13	1	17.11	300.0	6.34
	3	8.84	345.0	6.02		3			
	4	8.98	330.0	6.24		4	16.59	299.0	6.32
	6	9.15	333.0	5.96		6	16.86	300.0	6.39
	8	9.34	333.0	5.98		8	16.95	301.0	6.28
	9	8.94	343.0	5.96		9	17.1	301.0	6.28
	10	8.95	341.0	5.83		10	17.3	301.0	6.15
	13	8.98	342.0	5.8					
Mean Values:		9.1216	334.92	6.3788			14.675	273.18	6.465

Appendix D

Complete groundwater elevation data

Appendix D

Complete groundwater elevation data

Water Elevation Above MSL (m)								
Date	**FSP-1**	**FSP-2**	**FSP-3**	**FSP-4**	**FSP-5**	**FSP-6**	**FSP-7**	**Stream**
2/6/2015							273.39	273.35
2/27/2015								273.31
3/18/2015	275.08							
3/28/2015	275.05	276.30				274.47		273.37
4/4/2015	275.06	276.32			274.63	274.17	273.45	273.41
4/26/2015	275.07	276.42			274.63	274.47	273.47	273.44
5/13/2015	275.09	276.44			274.64	274.48	273.68	273.66
6/19/2015	275.04	276.38			274.62	274.44	273.48	273.45
8/20/2015	275.00	276.15			274.66	274.46	273.40	273.36
9/18/2015	274.99	276.12	274.97	275.88	274.58	274.44	273.38	273.34
9/19/2015	275.04	276.16	275.02	275.90	274.69	274.53	273.44	273.40
10/18/2015	275.01	276.16	275.01	275.91	274.64	274.46	273.36	273.32
11/20/2015	275.04	276.26		276.01	274.70	274.48	273.42	273.37
12/5/2015	275.07	276.36	274.95	275.94	274.67	274.48	273.51	273.48
1/6/2016	275.07	276.34	275.12	276.08		274.47	273.44	273.41

Appendix E

Complete stream stage and discharge data

Appendix E

Complete stream stage and discharge data

Date	**Stream Discharge**	**Stage (m)**
2/6/2015	0.47	273.35
3/28/2015	0.63	273.37
4/4/2015	0.70	273.41
5/13/2015	1.53	273.66
6/19/2015	0.98	273.45
8/20/2015	0.42	273.36
9/18/2015	0.36	273.34
9/19/2015	0.49	273.40
10/18/2015	0.35	273.32
11/20/2015	0.58	273.37
12/5/2015	0.85	273.48
1/6/2016	0.70	273.41

Appendix F

Complete seepage meter data

Appendix F

Complete seepage meter data

Diffuse Discharge		Spring Discharge (cm/s)			
Site	Discharge (cm/s)	Spring 4	Spring 5	Spring 6	Spring 8
1	$3.15 X 10^{-6}$	0.00914	0.00323	0.00625	0.00896
2	$2.03 X 10^{-6}$	0.00762	0.00415	0.00671	0.00948
3	$1.72 X 10^{-7}$	0.00896	0.00274	0.00482	0.00954
4	$1.40 X 10^{-6}$	0.0064	0.0078	0.00646	0.00988
5	$4.51 X 10^{-7}$	0.00503	0.00689	0.0061	0.00878
6	$4.14 X 10^{-6}$	0.00814	0.00802		0.00835
7	$4.80 X 10^{-6}$	0.00616	0.00841		0.00695
8	$5.15 X 10^{-5}$	0.00914	0.0078		0.00641
9	$6.60 X 10^{-5}$	0.00921	0.00646		0.00847
10	$1.42 X 10^{-4}$	0.0101	0.00634		0.00817
11	$3.44 X 10^{-6}$	0.0101	0.00555		0.00829
12	$1.13 X 10^{-4}$	0.00914	0.00518		0.0086
13	$5.83 X 10^{-7}$	0.00732	0.00524		0.00832
14	$2.06 X 10^{-7}$	0.00732	0.00579		0.00811
15	$3.25 X 10^{-6}$	0.00725	0.00594		0.00814
		0.00689	0.00585		
		0.00744	0.00616		

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