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Examining Transmission Loss Availability for Basin Aquifer Recharge from Perennial Streams in the Chuska Mountains on the Navajo Nation

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by

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Abstract

Stream transmission losses due to infiltration from semiarid, perennial streams are important processes that can help water managers and users quantify aquifer recharge. Transmission losses are streamflow reductions that are due to infiltration through the streambed, evapotranspiration, and losses to the floodplain or streambanks (Shanafield, et.al, 2014). Transmission losses from infiltration will always be greater than the amount recharged bacause streamflow hat infiltrates into the streambed can take a variety of pathways other that recharge. This study considers transmission losses in Whiskey Creek, a perennial stream on the Navajo Nation in the Chuska Mountains. The objectives of this study are to determine what factors most greatly influence transmission losses due to infiltration along Whiskey Creek and where transmission losses that become water available for recharge are occurring along Whiskey Creek. Streamflow and other measurements were taken during field campaigns in May, July, October, and November of 2019. Establishing where Whiskey Creek transitions from a gaining stream to a losing stream was determined through synoptic stream gaging along Whiskey Creek's channel. On the losing reach of the stream, the installation of mini-piezometers was used to determine vertical hydraulic gradients. Diminishing flows along Whiskey Creek's losing reach were observed at all times of year. This pattern is indicative of increased infiltration and water available for recharge as Whiskey Creek transitions from a mountainous stream to a basin stream. Characteristics of soils and surface geology corroborate the trends conveyed by discharge and vertical hydraulic gradients. The soils present where transmission losses suggest that infiltrated water is being held in water-bearing, sandstone derived alluvium sediments or recharging shallow unconfined aquifers.

Introduction

The connectedness of lower order streams and groundwater is an overlooked and very important aspect of water resource management both at the local scale and as headwaters for major river basins. Studying surface and subsurface hydrology as a single process paints a more complete picture of an area's water supplies and budget. Establishing where streams are connected to the subsurface and characterizing specific reaches as gaining or losing is integral in constructing water budgets and efficiently managing water resources. When a stream transitions from gaining to losing, transmission losses, such as infiltration or evapotranspiration (ET) reduce streamflow (Schreiner-McGraw, A. P., & Vivoni, E. R., 2018). When streams are in a losing phase, infiltrated water becomes available for recharge. In semi-arid and arid mountainous regions basin aquifer recharge is usually concentrated near streams channels (Wilson & Guan, 2004).

In drier climates, mountainous regions are important because they typically receive highest amounts of precipitation in the forms of both snow and rain. In the Four Corners region, mountainous basins rely on perennial streams originating at higher elevations to deliver the majority of the water (Tsinnajinne, 2018). Precipitation in semi-arid mountainous regions are greatest in the winter (Tulley-Cordova, 2018). In the southwest, snowpack and aquifers are the two most effective ways to keep water in regions that frequently experience drought or lack water storage infrastructure while minimizing loss to ET or other transmission losses (Friedrich, et al., 2018). Reservoirs can be subjected to evaporative losses and can be costly to maintain infrastructure, thus groundwater storage is the most advantageous way of keeping water in and near the communities that need it (Friedrich, et al., 2018). Defining the linkage between snow-dominated perennial streams and basin aquifer recharge is paramount to creating accurate water budgets in arid and semi-arid regions, as well as establishing baseline infiltration rates during dry seasons.

The Chuska Mountains is the focus area for this project. The Chuskas are located on the Navajo Nation, the largest land-based federally recognized tribe whose boundaries lie within Arizona, New Mexico and Utah, on the border of Arizona and New Mexico (Figure 1). The unconfined portion of the Navajo "N"-aquifer, a large, deep aquifer that exists completely on the Navajo and Hopi reservations , and other surrounding shallow aquifers are present at the base of the Chuska Mountain range and are a primary source of drinking and irrigation water for nearby Navajo communities (Tsinnajinnie, 2018 and Navajo Nation/USBR, 2018). Whiskey Creek is one of four perennial, first order streams in the Chuska Mountains, with a drainage area of 28mi² delineated at the Navajo Nation Water Management Branch (NNWMB) stream gage (Tsinnajinnie, 2018).

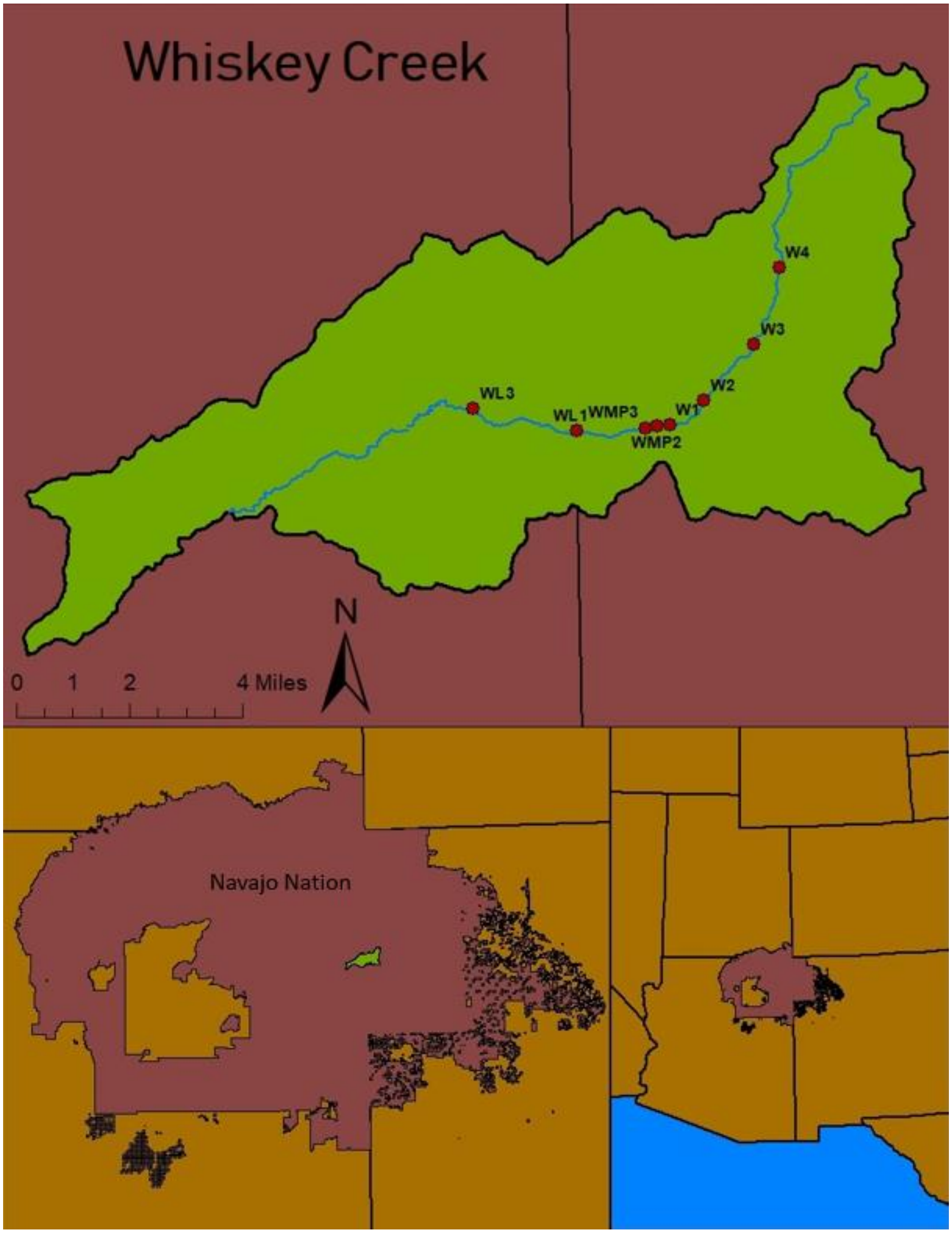

Figure 1. (Top)Whiskey Creek watershed boundaries with the 8 data collections sites indicated with red dots. (Bottom left) Reference map showing Whiskey Creek watershed in relation to the Navajo Nation. (Bottom right) Reference map for the Navajo Nation in relation the southwestern United States.

Whiskey Creek's flows are dominated by three different sources of water at different phases throughout the year, including snowmelt runoff in the spring, monsoon season rain events in late summer and early fall, and springflow generation due to hydrostratigraphy of the region during the winter and summer dry season (Tsinnajinnie, 2018). The transmission losses for these phases must be quantified and differentiated in order to estimate water available for aquifer recharge. Seasonality of infiltration in semi-arid mountainous regions is complex but increased snowfall at higher elevations coupled with several cycles of freezing and melting in the winter typically brings higher infiltration rates and streamflow when compared to the summer dry season (Ajami, 2012). Prior research in the region from (Tsinnajinnie, 2018) also showed evaporative losses directly from the stream are negligible via geochemistry measurements and end-member mixing analysis; however, any evaporative losses taking place in the subsurface or transpiration losses are still possible uses of water that infiltrates into the subsurface through the streambed. Understanding the role of perennial streams and providing estimates of water available for recharge to surrounding aquifers is extremely important for efficient and sustainable water management in rural and arid regions.

Mountain block hydrology and mountain front recharge play a fundamental yet often ambiguous roll in replenishing arid regions' groundwater supply (Wilson & Guan, 2004). Mountain front recharge is the process of water originating or precipitating in mountain ranges and contributing to the recharge of the basin aquifers either from direct groundwater and geological connection between the mountain block and basin or delivered via streams (Wilson & Guan, 2004). The ambiguity often associated with mountain front recharge is due to the lack of research done on the role piedmont slopes have as potential recharge areas (Schreiner-McGraw, A. P., & Vivoni, E. R., 2018). In arid regions, especially on the Navajo Nation where deep well and groundwater data is limited, and vadose zones can be deep; the unknown factor is how much of the streambed infiltration is recharging aquifers and or replenishing the water table rather than staying in the vadose zone to be lost to evapotranspiration. Infiltrated water is partitioned to several processes including being used by plants via transpiration, being lost to vadose zone evaporation, being stored in the unconfined zone, and deep percolation and recharge to aquifers (Figure 2). The uses of infiltrated water are dependent on a number of environmental characteristics including soil, underlying geology, climate, and vegetation. Although losses due to multiple processes are possible, this study focuses on the factors that contribute to transmission losses via streambed infiltration. Understanding these factors will provide an increased understanding of how much water is available for recharge from perennial mountainous streams.

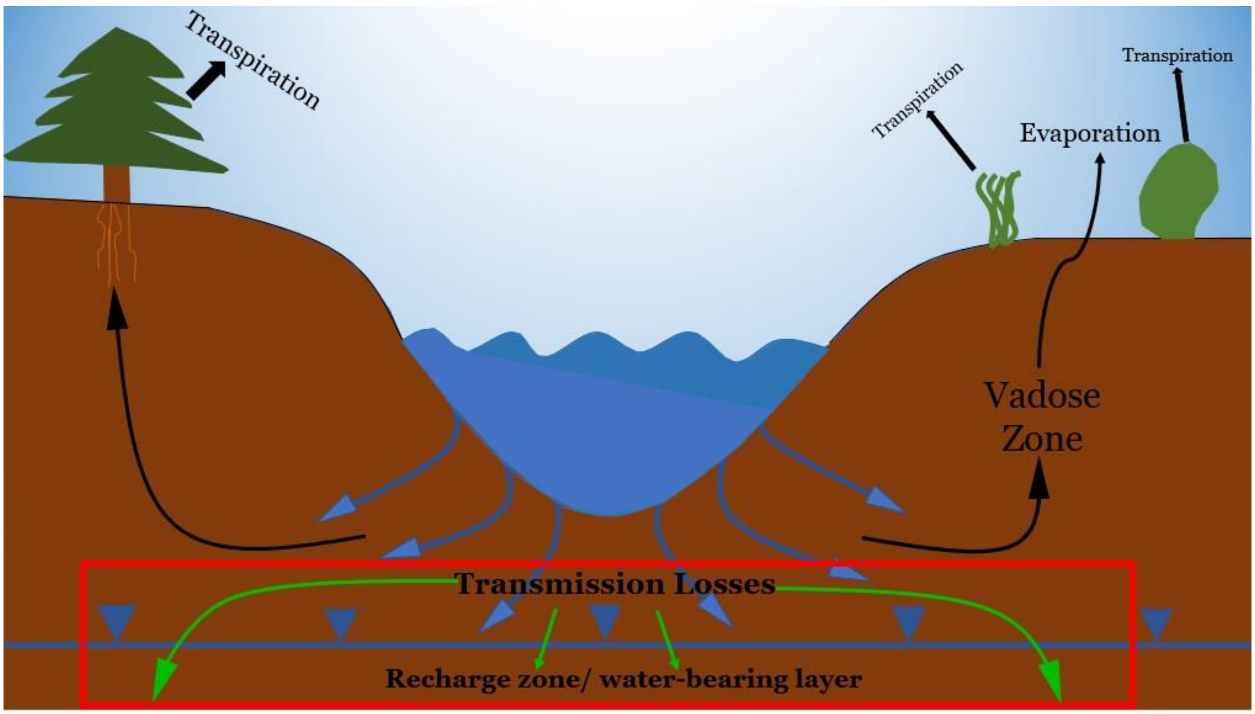

Figure 2. Conceptual model illustrating how transmission losses can partition into different pathways. Blue arrows show infiltration into the subsurface. Green arrows show transmission losses that contribute to recharge or fortify the water table. The black arrows show transmission losses that do not contribute to recharge, and the red box highlights the process this study focuses on: infiltration into the subsurface and water bearing sediments below the root and vadose zone.

Water resources on the Navajo Nation have an elevated importance, from a culture and steward perspective but also out of necessity. Water resources on the Navajo Nation are strained from many different directions with delivery infrastructure being a major contributor to stresses, 40% of Navajo families must haul their water to their home from wells (Navajo Nation Department of Water resources, 2003). Farming is a cornerstone of Navajo communities and economy, and agriculture stability is highly dependent on the nation's water resources (Navajo nation Department of Water resources, 2003). With many communities in the process of developing watershed management plans and water budgets the more information about groundwater recharge and surface/subsurface connectivity that is available the more effective these plans will be.

The overarching research question for this study is: What factors influence water made available for recharge from transmission losses along Whiskey Creek's losing reach?

This question will be addressed using the following subsidiary research questions:

- How do transmission losses on Whiskey Creek vary seasonally?
- What is the spatial pattern of transmission losses along Whiskey Creek?
- How do physical or geological characteristics such as soils affect spatial and seasonal variability of transmission losses on Whiskey Creek?

Answering these questions will help to better understand Whiskey Creek's potential contributions to basin aquifer recharge. This study will not focus on vegetative or evaporative losses, but it is recognized that analyzing the vegetation near the river, hydraulic conductivity of the streambed and floodplain, and the depth of the vadose zone would help with the overall understanding of the recharge processes along Whiskey Creek. This study will examine where, when, and how much of Whiskey Creek's streamflow is infiltrating back into the subsurface along its losing reach by using discharge measurements and calculating vertical hydraulic gradient from mini-piezometer readings.

When studying low order streams and their interactions with the subsurface, especially in regions where communities rely on groundwater as their primary sources of water, the complexities and minutiae of streamflows, climate, and surface and underlying geology is accentuated. Knowing how much water is available for aquifer recharge is a crucial variable for developing water budgets and watershed management plans.

Study Site Description

Whiskey Creek is the only undammed stream of the four-perennial stream in the Chuskas. The Chuska Mountains' geology is the primary driver of Whiskey Creek's perennial flows. The mountains are capped with the highly permeable Cenozoic Chuska Sandstone formation (Figure. 3) that absorbs a portion of each year's snowpack (Tsinnajinnie, 2018). The Chuska Sandstone average thickness is 1000 feet, and the formations that underly the Chuska Sandstone are Jurassic and Triassic formations. These underlying formations experienced hundreds of millions of years of folding, faulting, eroding, and depositing before the Chuska Sandstone formed (Harshbarger et al., 1954). Cretaceous rocks are only present in the southern and eastern parts of the Chuska Mountains indicating a period of powerful erosive forces during the time prior to the Chuska Sandstone formation (Harshbarger et al., 1954). Subsequently, an angular unconformity is present beneath the Chuska Sandstone and is the principle reason for the variability underlying the Chuska Sandstone (Harshbarger et al., 1954). The underlying formations consist of the Jurassic Morrison formation (claystone, siltstone, sandstone, and limestones), the San Rafael Group (sandstones, siltstones, and limestones), the Triassic Wingate Sandstone, and the Chinle Formations (predominantly siltstone), all of which act as a confining layer in the Chuska Mountains (Harshbarger et al., 1954). The water that is absorbed by the Chuska Sandstone flows through the formation before it eventually meets one of these low permeability and porosity formations and is forced out of the formation resulting in springflow generation and Whiskey Creek's baseflow (Harshbarger et al., 1954). Along Whiskey Creek, the surface geology is also peppered with different formations (Figure 4) that have different due to the uplifting and folding of these formations (Tsinnajinnie, 2018).

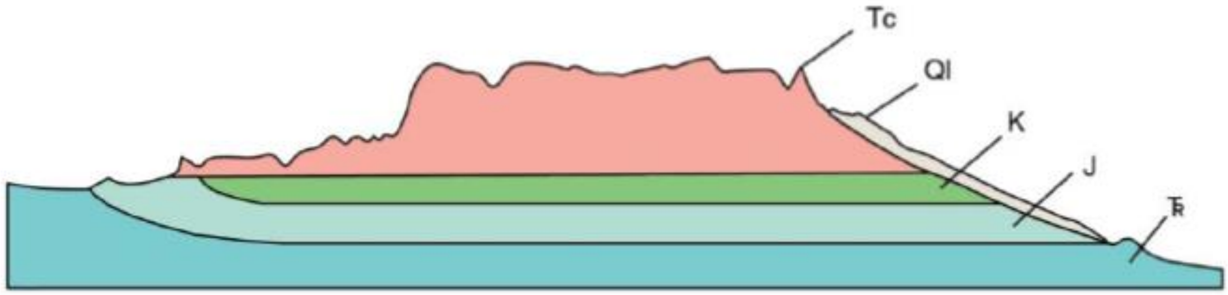

Figure 3. Generalized Chuska Mountain geology cross section, facing north. Chuska Sandstone(Tc) caps the mountain with less permeable Jurassic(J) and Triassic (Tr) formations underlying the Chuska Sandstone. Figure from (Tsinnajinnie, 2018).

The basin's geological stratigraphy is just as important as the mountain geology for characterizing Whiskey Creeks hydrology; as Whiskey Creek transitions from gaining to losing, the partitioning of infiltration largely rests on the permeability of the basins underlying geology, which is highly variable (Harshbarger et al., 1954). The Chinle formation, which underlies Whiskey Creek along the losing reach also has a low permeability, and acts as a shallow confining layer, but may also contribute to holding infiltrated water from transmission losses (Tsinnajinnie, 2018). Whiskey Creek is believed to be hydrologically connected to a shallow water-bearing alluvium layer which overlies the Chinle formation, but there is no clear evidence of these layers connecting to the larger, deeper basin aquifers such as the N-aquifer due to the low porosity of many surficial formations (Harshbarger et al., 1954).

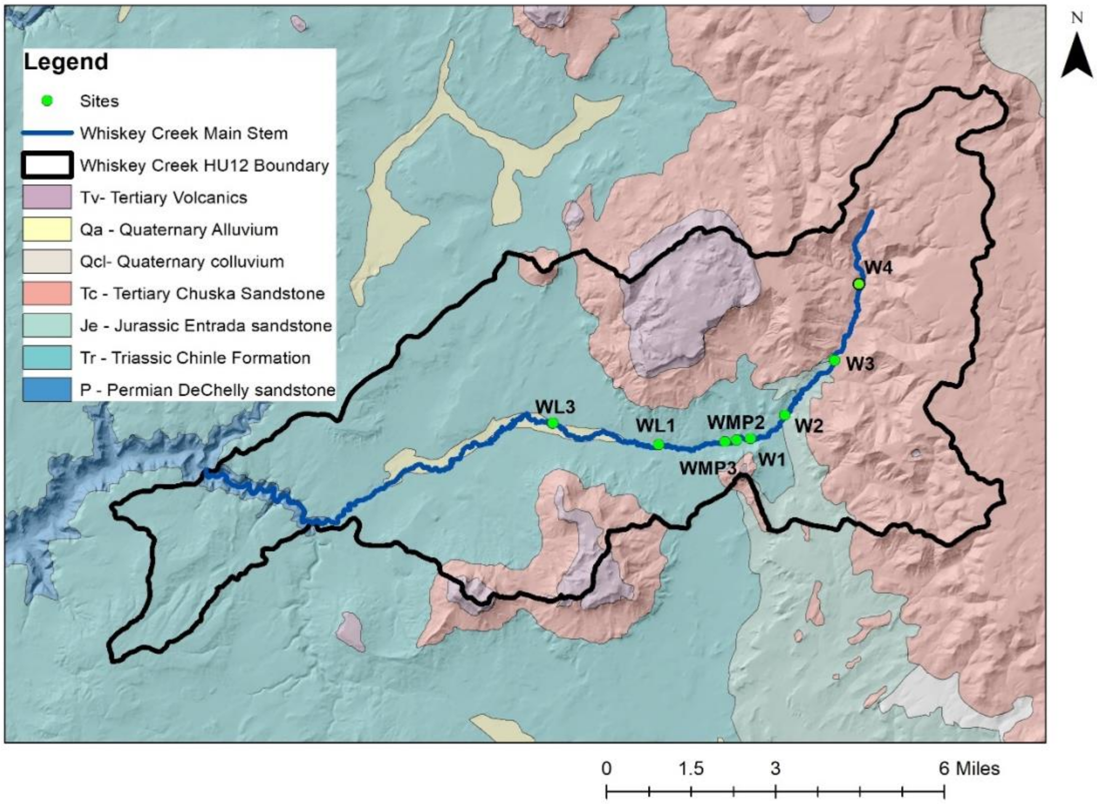

Figure 4. Surface Geology of Whiskey Creek watershed, the green dots show where the data collection sites are in relation to the underlying geology

Whiskey Creek's yearly hydrograph shows peak flows during snowmelt runoff season that are on average ten times higher than baseflow season, so quantifying infiltration rates when there is more water in the channel is extremely important to telling the story of the Chuska Mountain's and Whiskey Creek's surface and groundwater hydrology. Whiskey Creek's flows peak in April due to snowmelt runoff, and flows from March through May account for 62% of Whiskey Creek's total yearly discharge on average (Figure 5).

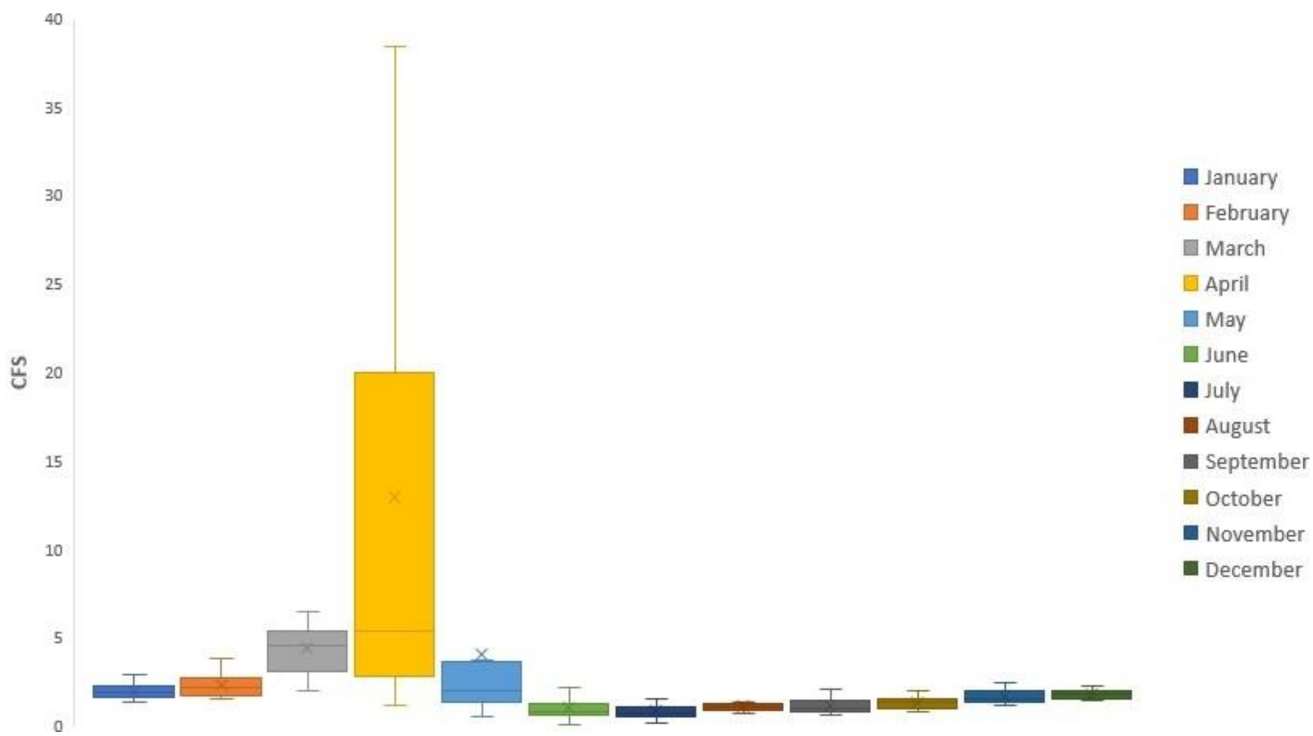

Figure 5. Daily discharge data in cubic feet per second (cfs) per month at Whiskey Creek (W1) between 1997-2016. The 'x' represents the average cfs, the line is the median, the box shows the 25^{th}-75^{th} percentile, and the whiskers show the full range of measurements (data provided by the Navajo Nation Water Management Branch)

A total of 8 different sites along Whiskey Creek were established for stream gaging, water sample collection, and vertical hydraulic gradient measurements (Whiskey 4, Whiskey 3, Whiskey 2, Whiskey 1, Whiskey MP2, Whiskey MP3, Whiskey L1, and Whiskey L3) as shown in Figure 1 and 6. (Tsinnajinnie,2018) established Whiskey 4, 3, 2, and L1. Whiskey 1 has been the stream gaging site for the Navajo Nation Water Management Branch, where a flume and pressure transducer are used for measuring daily discharge. The reach between Whiskey 1 and Whiskey L1 is also considered the transition zone for Whiskey Creek. Tsinnajinnie (2018) showed that Whiskey Creek is gaining between Whiskey 1 and Whiskey L1. Sites Whiskey MP2 and MP3 were established for this study to accurately pinpoint where Whiskey Creek transitions from a gaining stream to a losing stream. Whiskey L3, which is the furthest downstream site was established because of its road accessibility and its placement in the mountain basin.

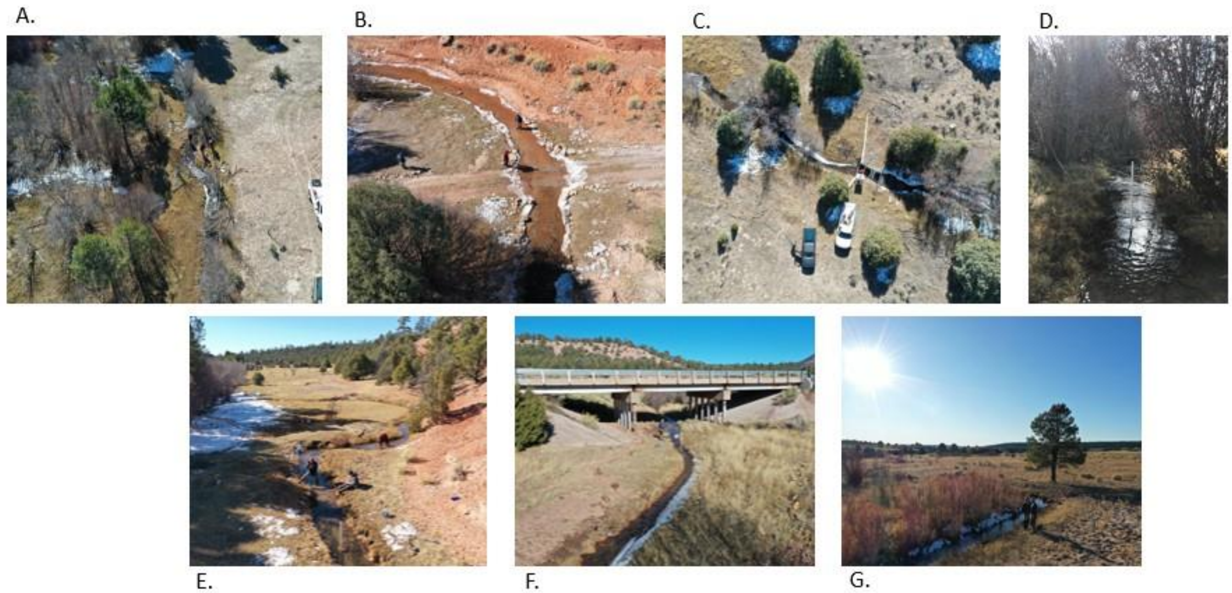

Figure 6. Data collection site photos: A. Whiskey 3, B. Whiskey 2, C. Whiskey 1, D. Whiskey MP2, E. Whiskey MP3, F. Whiskey L1, G. Whiskey L3.

Methods

To calculate infiltration losses that make water available for recharge many values and stream characteristics must be known: streamflow rates, where the stream is gaining and losing, and soil and geological characteristics.

Reach Length Water Balance

This technique is a simple, cost effective way to measure and map transmission losses along a perennial stream. The discharge of an upstream cross section of the river is measured and simply subtracted from the downstream flow rate. In a streams' gaining reach, discharge measurements should increase further downstream. If the upstream discharge measurement is greater than the downstream measurement, the stream has transitioned from gaining to losing, and should continue to lose from that point on. The difference between the two flow rates is the amount lost to transmission losses or gained due to contributions from groundwater or a larger drainage area, with the stipulation that flow is steady, and no tributaries are adding to the flow in between measurement points (Shanafield, et al., 2014).

Installation of Mini-piezometers

A 1 inch diameter and 5 foot PVC pipe with 30 holes drilled in the bottom 6 inches of the pipe was installed into the stream bed by hammering a rod into the stream with a post hole driver, pulling out the rod and inserting the mini-piezometer into the hole. Water inside the piezometer is siphoned out manually with a tube. Once emptied and refilled, 3 measurements are taken with a water level sounder: top of the piezometer to the stream bed, top the piezometer to the stream surface, and top of the piezometer to the water level inside the piezometer. Every 5 minutes the water level on the inside of the piezometer is measured until it is stabilized. The difference between the water level inside the piezometer and the water surface is key to calculating vertical hydraulic gradient. When the water level in the piezometer is lower than the water surface of the stream it is losing, and when the water level in the piezometer is higher than the water surface of the stream it is gaining.

Vertical Hydraulic Gradient

Following the methods laid out in (Baxter et al., 2002) vertical hydraulic gradient (VHG) was calculated using the equation VHG= $\Delta h/\Delta l$ where Δh is the difference between the water level of the stream and the water level inside the piezometer and Δl is the depth from the streambed to the top of the 15 cm holed segment. If the Δh is negative the stream is losing, and if positive the stream is gaining (Figure 7).

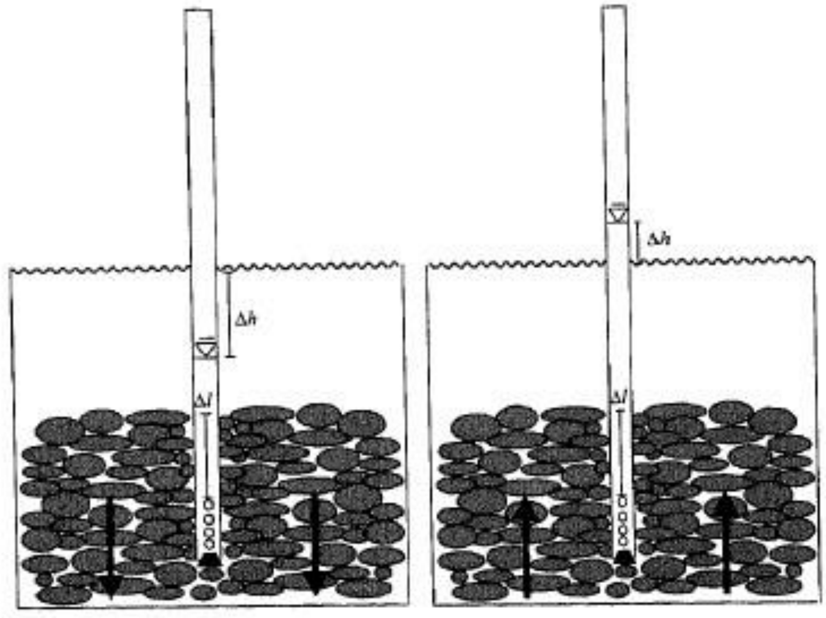

Figure 7. Illustration of VHG variables according to (Baxter et al.,2002). The image of the left shows *Δh* of a losing stream and the right image shows conditions for a gaining stream

Soil Profile Analysis

Upon completion of collection of hydrologic field data, soil data was gathered using the United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) web soil survey tool. Collection sites' GPS points were searched in the "area of interest" (AOI) quick navigation tool, a polygon or rectangle was drawn on the web soil survey interactive map around the GPS data collection point and the AOI was generated. The soils map was then selected and the soil unit names were identified by the soil unit symbol on the map and in the legend. Soil units were then characterized by the USDA NRCS Soil Survey reports for the region.

Results & Discussion

How do transmission losses on Whiskey Creek vary seasonally?

There were 4 field campaigns to the Chuska Mountains in 2019 (May, July, October, and November) to collect data at different phases of streamflow at Whiskey Creek. Figure 8 shows the discharge data collected during these trips, which continue to show a transition of Whiskey Creek from a gaining stream to a losing stream between Whiskey 1 and Whiskey L1. There were, however several variables and extenuating circumstances affecting the variability of several discharge measurements from Whiskey 1 to Whiskey L3.

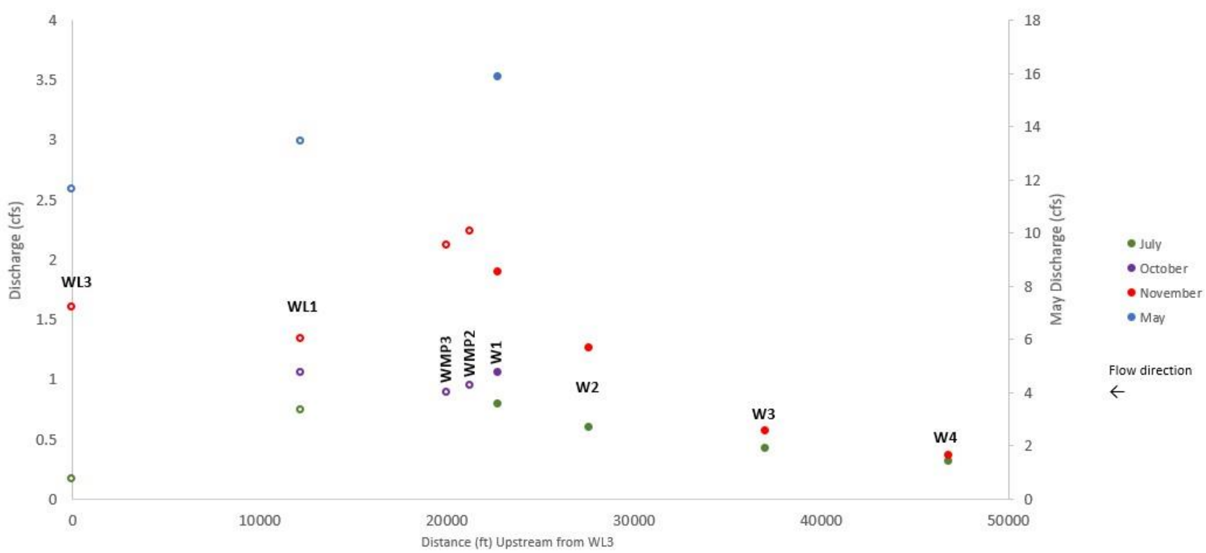

Figure 8. Data set of all stream gaging on Whiskey Creek, the x-axis is to scale- with distance between each sampling site. Hollow data points indicate a losing reach. The left y-axis is for the July, October, and November data sets and the right y-axis is for the May, snowmelt runoff data set. There is a clear pattern of increasing flow to Whiskey 1, and a decrease with minor undulations after Whiskey 1 on the losing reach.

Snowmelt runoff season in May contributed the most infiltration by volume between Whiskey 1 and Whiskey L3, with a loss of 4.24 cfs along the reach. The attributing factor is there is 8 to 20 times more water in Whiskey Creek's losing reach during snowmelt runoff season than summer and winter dry/baseflow seasons. In July, right before monsoon season began, the lowest discharge measurements of entire data set were collected. The October data set saw a slight increase in discharge of 0.16 cfs between Whiskey MP3 and Whiskey L1 due to small rain event that occurred while measurements were being taken. The November discharge data deviated the most from the pattern established by the rest of the data set, an increase in discharge of 0.34 cfs between Whiskey 1 and Whiskey MP2, and then also an increase in discharge of 0.26 cfs between Whiskey L1 and Whiskey L3. This is attributed to the conditions on the day we collected that data. On the November collection day, discharge measurements were affected by the diurnal heat fluctuations as well as an approximately 3 inch ice layer that had to be manually broken up while also melting in 60°F midday temperatures. These variables likely contributed heavily to differences in the November discharge measurements.

When analyzing the water mass balance from Whiskey 1 to Whiskey L3, and converting the difference in cfs to an acre-ft per day value, it becomes apparent much more total water is being lost to transmission losses in May than in July and November (Table 1). However, we see that during the summer baseflow season, before large monsoonal storms in July (Figure 9), a much larger percent of the streamflow at Whiskey 1 is being infiltrated by the time it reaches Whiskey L3. This is not the case for the November streamflow measurements due to the aforementioned diurnal freezing and thawing occurring that day.

Month	May	July	November
Reach	W1 to WL3	W1 to WL3	W1 to WL3
cfs	4.24	0.63	0.30
acre-ft/ day	8.40	1.25	0.60
% lost	0.27	0.79	0.16

Table 1. Shows difference in discharge from Whiskey 1 to Whiskey L3. Additionally, assuming flow was constant for a 24-hour period on the data collection day, the difference in cfs is

converted to acre-ft /day. Lastly, the percentage lost was calculated with the flows at Whiskey 1 representing 100 percent of the losing reach's flow.

Whiskey Creek's precipitation in 2019 also represents the seasonality of Whiskey Creek's streamflow. The precipitation chart shows the accumulation of snow from December to March, which on the discharge graph is represented by the high flows in early May. Summer and winter baseflow season are also easily identifiable. The late arrival of monsoon season extended the summer baseflow season into late August which is exceptionally late compared to prior years. Winter baseflow season appears to start in October, however, during the October field campaign there was a precipitation event that affected discharge measurements that does not appear on the precipitation graph. This shows the spatial variability of precipitation in the region, although it was raining near where we were collecting data in October, the Snotel site did not capture it.

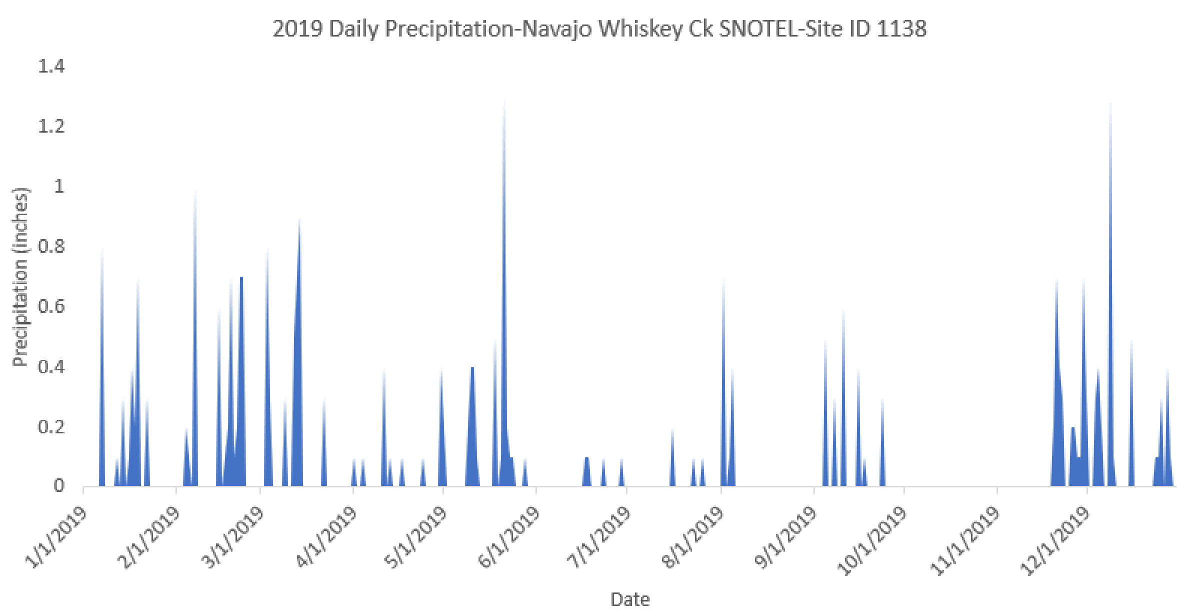

Figure 9. Shows precipitation events at Whiskey Creek in 2019. Monsoon season started abnormally late was irregular. The October rain event is also visible on this graph.

Sankey diagrams allow for visible comparison of Whiskey Creek's water budget during snowmelt season (May) and summer baseflow season (July), even though much more streamflow by volume is lost to transmission losses in May, the July flows lose almost 80 percent of Whiskey 1 flows by the time the water arrives at Whiskey L3 (Figure 10).

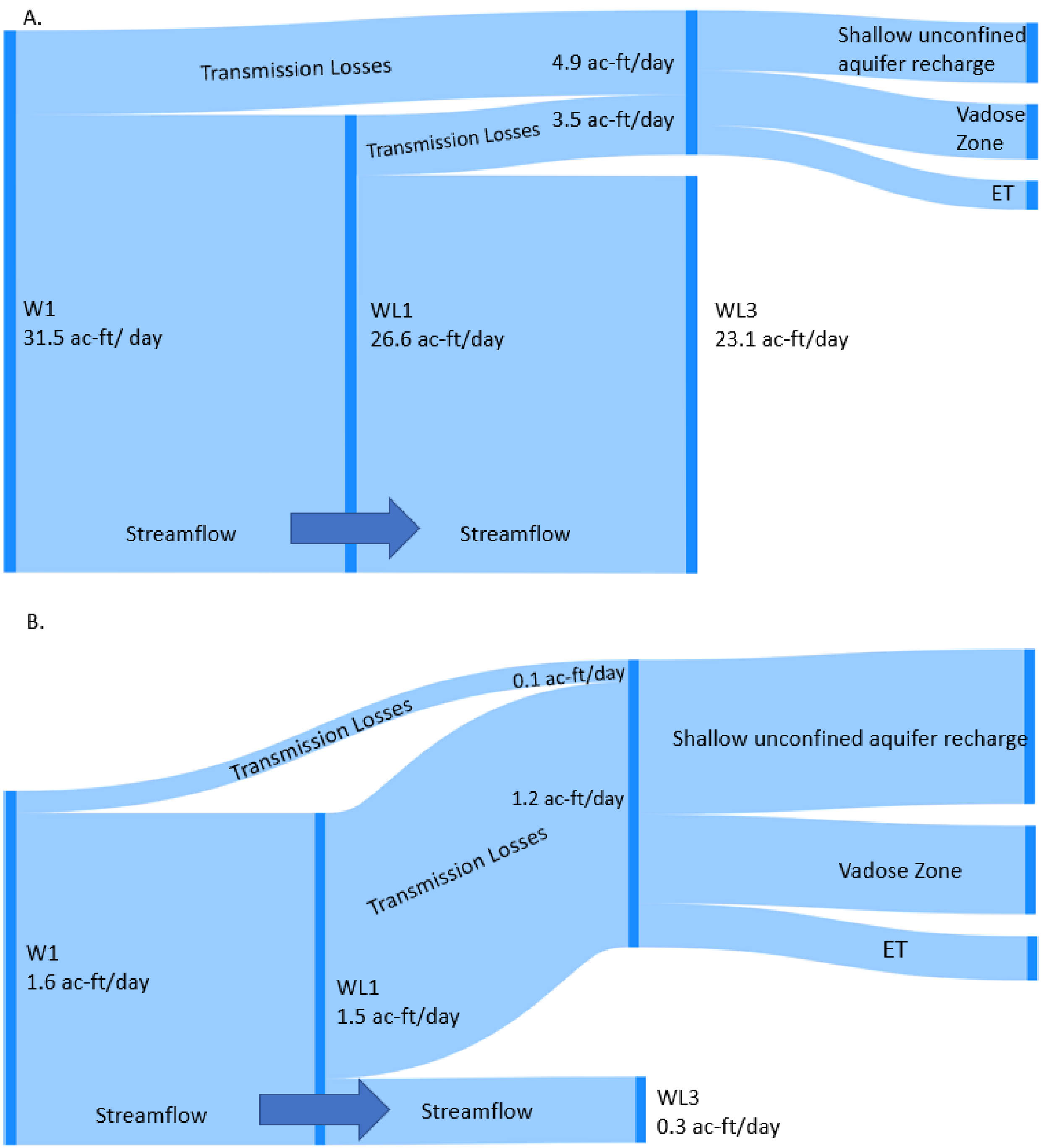

Figure 10. Sankey diagrams for snowmelt runoff season (A) and July baseflow (B), with amount of water represented in acre-feet per day. The blue arrow denoted flow direction, the three transmission loss uses are not shown to scale, and the Sankey diagrams show changes between Whiskey 1, Whiskey L1, and Whiskey L3.

What is the spatial pattern of transmission losses along Whiskey Creek?

There is an apparent trend shown from the discharge data in this study that is consistent with the results from Tsinnajinnie (2018) that Whiskey Creek's transition from gaining to losing is between Whiskey 1 and Whiskey L1. Field measurements to this study showed that transition zone was more accurately determined to be closer to Whiskey 1. Vertical hydraulic gradient measurements corroborate what the discharge measurements show. Between Whiskey 1 and Whiskey MP2 the unitless VHG transitions from positive to negative indicating Whiskey Creek's transition from gaining to losing (Figure 11) VHG drops steeply in the half mile reach from Whiskey 1 to Whiskey MP3, dropping from 0.11 to -0.6. VHG gradient begins to increase between Whiskey MP3 and Whiskey L1 but never retransitions to gaining. Finally, in the last reach between Whiskey L1 and Whiskey L3 (approximately 2.3 miles), VHG drops dramatically from -0.06 to -1.56. Based on VHG measurements, Whiskey MP3 and Whiskey L3 experiences the largest amount of infiltration and thus are the areas where there is the most water available for recharge along the studied reach of Whiskey Creek.

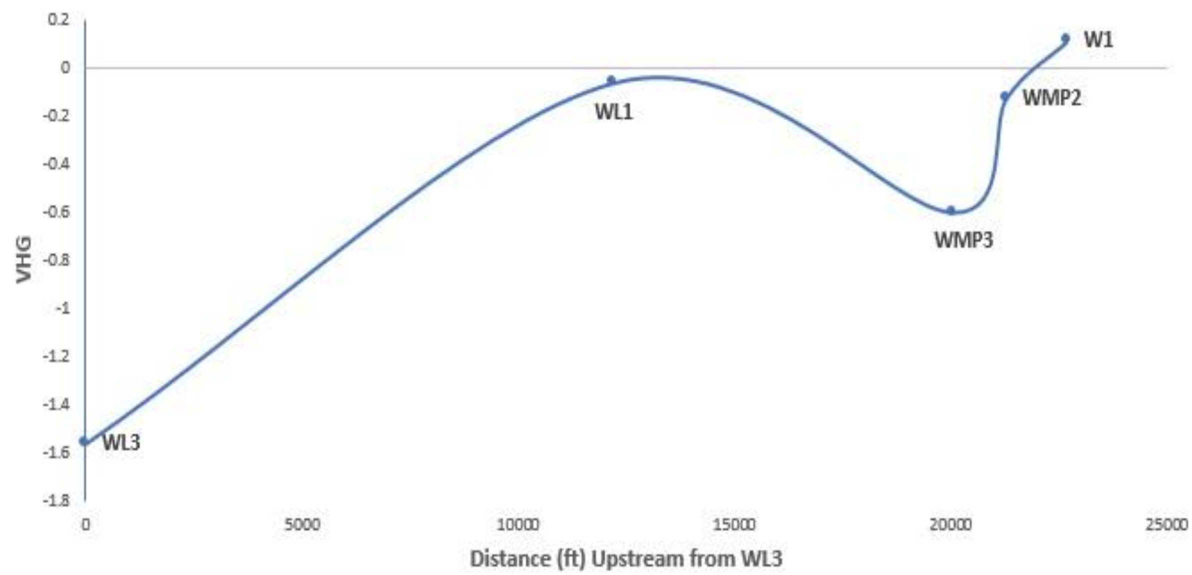

Figure 11. Chart showing VHG along the losing reach of Whiskey Creek (Whiskey 1 to Whiskey L3). VHG was only collected in October and November, this chart shows that average of the 2 sets of data.

VHG declined substantially in a very short distance between Whiskey 1 and Whiskey MP3, this can be attributed to the presence of several beaver dams on that reach that created backwaters, slowed flows, and possibly caused focused recharge. The presence of more conductive soils also contributed to the increased infiltration along this reach. The increase in VHG along the losing reach, between Whiskey MP3 and Whiskey L1 is likely due to the location of Whiskey L1, it is located very close to bridge and road, compaction of the soils near Whiskey L1 likely played a role in the increase VHG as the soils themselves indicate infiltration is likely at this site.

How do physical or geological characteristics such as soils affect spatial and seasonal variability of transmission losses on Whiskey Creek?

The Chinle Formation represents the dominant surface geology of the losing reach of Whiskey Creek has low permeability and implies that recharge is happening in shallow aquifers and water-bearing alluvial soils. However, Whiskey L3 is located within an outcrop of quaternary alluvium (Figure 3). Weathered and eroded Chuska Sandstone sediments is the parent material for the water-bearing alluvium soils that underly Whiskey Creek (Harshbarger et al., 1954). Thus, the Chuska Sandstone that plays an extremely important role in spring flow generation and the perennial nature of Whiskey Creek is also integral to transmission losses downstream.

The characteristics of the soil units present along Whiskey Creek support the discharge trends and the VHG results (Table 2). At Whiskey 4 and 3 the Bikeyah- Berland Families Complex is predominately made up a fine-sandy loam but is very shallow with bedrock being 25 inches from the surface. The soil unit at Whiskey 2 is Verite Manuelito Complex that has a shallow clay loam layer with bedrock only 11 inches from the surface. Whiskey 1, the transition zone from gaining to losing, has a much deeper and coarser soil profile called the Klizhin-Sandark Families Complex that consists of a coarser loam and eventually sand 5 feet deep which makes infiltration much more likely. At Whiskey MP2 the Klizhin- Sandark Families Complex and Kachina-Evpark Family-Gladel Family Complex soil units are present. The latter unit has a sandy clay loam that is 30 inches deep with bedrock directly beneath it, the shallower soils and presence of clay could explain the gradual decrease in VHG between Whiskey 1 and MP2. At Whiskey MP3 Oxyaquic Haplustolls are present, which is alluvium derived from sandstone and shale. It is extremely well mixed and its keynote characteristic is a sandy Cg layer with the g indicating gleying or saturation. Oxyaquic Haplustolls are defined as soils that are “saturated with water within 100cm of the mineral soil surface for 20 days or more consecutively” (USDA: Soil Taxonomy, 1999). Whiskey L1’s soils are deep, well mixed fine-sandy loams and loamy sands that are very permeable and likely conducive to infiltration. Lastly, at Whiskey L3, the Oxyaquic Haplustolls are also present here and seem to be synonymous with infiltration and shallow, unconfined aquifer recharge.

Site	Soil Unit Name	Classification	Parent Material	Profile
W4	Bikeyah-Berland Families Complex	course-loamy/ loamy mixed	alluvium derived from sandtone	0-25 inches- fine-sandy loam 25 inches- Bedrock
W3	Bikeyah-Berland Families Complex	course-loamy/ loamy mixed	alluvium derived from sandtone	0-25 inches- fine-sandy loam 25 inches- Bedrock
W2	Verite Manuelito Complex	fine-loamy/ loamy mixed	eolian deposits & stream alluvium derived from sandstone & shale	0-11 inches- clay loam 11 inches- Bedrock
W1	Klizhin-Sandark Families Complex	course-loamy/ sandy	alluvium & residuum weathered from sandstone	0-47 inches- fine-sandy loam 47-60 inches- loamy- fine sand 60-70 inches- Sand
WMP2	Klizhin-Sandark Families Complex/ Kachina-Evpark Family/ Gladel Family Complex	course-loamy/ sandy	eolian deposits derived from sandstone/ alluvium & residuum from weathered sandstone & shale	0-47 inches- fine-sandy loam 0-2 inches- loam 47-60 inches- loamy- fine sand 2-30 inches- sandy-clay loam 60-70 inches- Sand 30 inches- bedrock (shallower in some places)
WMP3	Oxyaquic Haplustolls-Riverwash Complex	well mixed clay loam to course sand	alluvium derivd from sandston & shale	0-50 inches- loam to loamy-fine sand 50-60 inches- gleyed sand (Cg layer)
WL1	Zia Sandy Loam	coarse-loamy	eolian deposits & stream alluvium derived from sandstone & shale	0-80 inches- fine-sandy loam to loamy sand
WL3	Oxyaquic Haplustolls-Riverwash Complex	well mixed clay loam to course sand	alluvium derivd from sandston & shale	0-50 inches- loam to loamy-fine sand 50-60 inches- gleyed sand (Cg layer)

Table 2. Soil chart for all 8 data collection sites with soil name, classification, parent material, and generalized soil profile.

Conclusion

What factors influence water made available for recharge through infiltration via transmission losses along Whiskey Creek's losing reach?

Whiskey Creek's infiltration along its losing reach is controlled by a number of variables. Transmission losses are greatest during snowmelt runoff season. Thus, the amount of infiltration and water available for recharge is heavily dependent on seasonality. Based on the flow data and the significant change in VHG between Whiskey L1 and Whiskey L3, it is likely that this reach is where infiltration is highest and has the most potential for recharge. The presence of the prolongedly saturated Oxyaquic Haplustoll- Riverwash Complex soil unit at Whiskey MP3 and Whiskey L3, the sites with the lowest VHG confirms shallow unconfined alluvial aquifer recharge is happening at those locations. The variability in the underlying geology along Whiskey Creek, is the most important variable when considering potential for deep aquifer recharge. Whiskey L3 is located within an outcrop of quaternary alluvium, but surface geology is largely dominated by the Chinle Formation. The presence of quaternary alluvium at Whiskey L3 likely contributes to the propensity for infiltration at this site, however, the low permeable nature of the Chinle Formation likely inhibits percolation to deeper aquifers. This study provides a first look at where and when Whiskey Creek's recharge likely occurs. Although there were weather and geomorphic variables that affected the streamflow and VHG measurements it is certain that Whiskey Creek is a losing stream below Whiskey 1 and Whiskey MP3 and Whiskey L3 are the sites where infiltration is greatest. Seasonally, snowmelt runoff on Whiskey Creek contributed the most to water available for recharge.

Limitations

Our methodology was not developed to explicitly differentiate the uses of the infiltrated water but to find where and when infiltration and recharge potential is the highest and why. We recognize the absence of continual monitoring and measuring with this study and are aware of the limitations of point data collection and the dangers of interpreting and extrapolating trends with point data collection. Road and permission access also led to additional limitation to establishing consistently spaces sample sites along the study reach of Whiskey Creek. However, this study provides a first look at where Whiskey Creek's recharge zones likely are, with patterns that do not vary based on volume of flow or time of year. Although there were weather and geomorphic variables that affected the streamflow and VHG measurements it is certain that Whiskey Creek is a losing stream below Whiskey 1 and Whiskey MP3 and Whiskey L3 are the sites where infiltration is greatest. Seasonally, snowmelt runoff on Whiskey Creek contributed the most to water available for recharge.

Implications & Future Work

Stable isotope samples were collected during each of the field campaigns but were not analyzed in time to be included in this study. Stable isotope analysis, as well as analysis using other environmental tracers, would provide a clearer understanding of the connection between infiltration losses and recharge. Further examination of losses due to evapotranspiration would also help to understand the water budget and to eventually quantify recharge in the Whiskey Creek Watershed.

The Navajo Nation Water Management Branch (NNWMB) has been monitoring and collecting hydrologic data on the Navajo Nation since the 1980's. The NNWMB's primary responsibility is to protect the nation's water rights and to restore and manage its watersheds and water resources. The NNWMB is underfunded and understaffed, and preliminary studies such as this one aid the NNWMB in fulfilling their responsibilities to the land and to their people.

Currently there are several Navajo Nation water user authorities developing watershed management plans. Being able to accurately predict transmission loss fate is a crucial component to the region's water budget. In order to make a viable water management plan an understanding of surface and groundwater connection especially in relation to the Chuska Mountain's perennial stream is crucial. As previously mentioned, Whiskey Creek is one of four perennial streams in the Chuska Mountains and is the only undammed stream. Similar studies on the other perennial streams must also be done to gain a broader understanding of the region's groundwater resources. Additionally, since the other perennial streams are dammed at different locations in relation to the mountains, Whiskey Creek can serve as a control for the other streams pertaining to transmission losses and the affect dams have on water available for recharge.

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