SOIL MOISTURE DYNAMICS OF MUHLY SEEPS IN A HILLSLOPE HOLLOW DURING LOW FLOW AND STORM CONDITIONS

by

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Introduction

Groundwater seeps are characteristic hydrological and ecological features of many landscapes. The unique chemical, physical and hydrologic context of groundwater discharging from seeps provides critical habitat for many wetland plant communities and invertebrate species. Seeps also contribute source water to streams, including many trout streams, which are important both ecologically and economically (Fermanich et al. 2006). However, while a number of studies examine seeps in terms of oil and gas production, few studies examine the hydrology of seeps. The most applicable literature assesses the cedar glade ecosystems of Kentucky and Tennessee, but focuses on the vegetative aspects rather than the hydrology (Norton 2010).

While seeps exist in a variety of environments, their extent and characteristics are poorly known. This study examines the hydrology of seeps dominated by Seep Muhly grass (*Muhlenbergia reverchonii*) in the Grand Prairie Ecoregion (Griffiths et al. 2004). Research on Muhly hillslope seeps (hereafter referred to as Muhly seeps) is limited, partially because most optimal study sites fall within the confines of privately owned land. Additionally, the hyperseasonal tendencies of Muhly seeps limit recognition since seeps may appear inactive and hydrologically irrelevant during the hot, dry portions of the year. As a result most research on Muhly seeps focuses solely on vegetation.

While the vegetation is not within the scope of this study, it is important to recognize that vegetation composition defines Muhly seeps. *Muhlenbergia reverchonii* dominates the Muhly seeps, along with predictably associated species, such as *Carex* *microdonta* and *Eleocharis occulta*, which tend to flourish in the wettest portion of the seep. These vegetative indicators help identify potential Muhly seep study sites and distinguish “intact” Muhly seeps.

Muhly seeps result where the interbedded limestone and marl geology of the Grand Prairie system outcrops on middle to lower slopes. As water filters down through fractured limestone, it encounters marls at shallow depths. The marls act as aquitards and divert the flow of water horizontally, forming seeps at the surface. The clayey soils also contribute to episodes of saturation and desiccation; after storms, the seeps may remain saturated for weeks, but during drought they can become completely dry (Burgess 2010). An associated barrens environment, normally located up or down slope of Muhly seeps, “often exists where either through erosion or deposition, a relatively thin layer of soil is present atop an intact layer of bedrock” (Williams 2008, 10).

Dyksterhuis (1946) provides the earliest known description of Muhly seeps, describing slopes with extremely shallow soils dominated by Muhly seep grass that became “seepy after heavy rains because soilwater running along the horizontal limestones is brought to the surface” (18). However, these same sites “become possibly the most arid sites of the slope by mid-summer,” making the name “Muhly seep grass” seem like a misnomer at times (Dyksterhuis 1945, 18). Hyperseasonal hydrologic systems that alternate between complete soil water saturation and periods of intense drought also exist in the tropical savannas of Venezuela (Sarmiento 1984; Sarmiento 2001). Observations of the same phenomenon occurred in Great Plains prairie streams, which “exist in a precarious balance between flood and drying,” but retain full ecosystem functioning during periods of saturation (Dodds 2004, 205), and in the Tennessee and Kentucky limestone cedar glades, with "thin soil, saturated in winter and early spring, with drought-like conditions during the summer" (Norton 2010, 9). Applying these same concepts to the Grand Prairie, Muhly seeps are classified as hyperseasonal systems (Burgess 2010).

This study focuses on seep micro-hydrology, deviating from both the scale and focus of traditional hillslope hollow studies. However, Dunne (1981) comments, "for some purposes…important questions about hillslope hydrology do not concern the production of stormflow, but…the moisture conditions on the hillslopes themselves" (229). Thus, traditional hillslope concepts still provide insight into the mechanisms behind Muhly seep soil moisture. When applied to a climate comparable to the Muhly seeps, the Variable Source Area (VSA) concept shows that hydrographs in more humid climates with thin soils and gentle slopes will be dominated by direct rainfall and return flow, with minimal subsurface stormflow (Hewlett and Hibbert 1967; Dunne 1981). Horton overland flow, usually observed in anthropogenically "disturbed" areas, should not be present in an unaltered Muhly seep environment (Dunne 1981, 271). Additionally, theories regarding formation of saturated wedges migrating upslope from streams are applicable to the soil moisture dynamics observed at Muhly seep sites.

However, applying traditional VSA and saturated wedge theories to Muhly seeps does not entirely explain the system hydrology. Initial observations in Texas suggest Muhly seeps are geologically controlled and hydrologically disconnected from the rest of the hillslope, with the wettest portions of the hillslope at the Muhly seeps (Burgess

2010). A number of studies provide descriptions of geologically controlled systems. Hewlett and Hibbert (1967) acknowledge that for small watersheds in humid environments, average soil mantle depth or depth to impervious stratum is a significant control. Additionally, Freer (2002) suggests that bedrock topography, rather than surface topography, could be the most important surface control over downslope water movement. Further research on hillslope hollow hydrology (McDonnell 2003; Hopp and McDonnell 2009) supports the existence of geologically controlled systems. Recent literature increasingly supports a shift from traditional VSA and saturated wedge theories to theories of geologically controlled systems.

Due to the extent of comparable Cretaceous Fredericksburg and Washita Group geology (Scott et al. 2003) within the Grand Prairie, results from this study could potentially apply across a sizeable area, representing a large-scale deviation from traditional hillslope hollow mechanisms. Further relevance of this study includes an interest in considering Muhly seep systems for possible wetlands delineation. Three key environmental parameters must be present to meet the criteria for wetlands delineation: hydric soils or soil formed under reducing conditions, wetland hydrology with periodic inundation, and hydrophytic vegetation (USACE Environmental Laboratory 1987). This study fulfills the hydrology and pedology parameters, while a concurrent study (Jue 2011) fulfills the vegetation parameter.

This study reports the results of an 8-month field investigation into soil moisture dynamics of Muhly seeps in a hillslope hollow during low flow and storm conditions.

The objectives of this study:

- Quantify soil moisture dynamics of Muhly seeps in a hillslope hollow during low flow and storm conditions;
- Determine how saturated wedges develop in response to hydrology and the Muhly seeps;
- Delineate hydrologic response of Muhly seeps during major storm events;
- Describe pedologic and geologic features associated with Muhly seeps.

Study site and methods

The study site is a United States Army Corps of Engineers (USACE) property located east of Benbrook Lake in Fort Worth, Texas (32°37’35” N, 97°25’ 31” W) (Figure 1). Elevation ranges from 730 to 740 feet above mean sea level. The soil survey map indicates Aledo gravelly clay loams are present at the crest of the transect grading to the Aledo-Bolar complex downslope (Figure 1). The Aledo gravelly clay loam series describes a gently sloping (1-8%) soil underlain by fractured limestone, which is well drained with moderate permeability and medium runoff (Ressell 1981, 13). The Aledo-Bolar complex occurs on steeper slopes (5-20%) relative to Aledo gravelly clay loam series. The Aledo series is typically associated with limestone, while the Bolar series is typically associated with marls. It is underlain by soft fractured limestone and is well drained with moderate permeability and rapid runoff (Ressel 1981, 14). Duck Creek Formation dominates bedrock at the study site, consisting of thin, alternating white chalky limestone and yellowish-white marls (Hill 1901; Markovchick 1978; Scott 2003). The study site represents a minimally grazed enclosure of the Grand Prairie with minor human impact resulting from recreational activities; therefore, historic descriptions of the Grand Prairie are relatively applicable. Hill (1901) describes the Grand Prairie's "gently sloping, almost level, and usually treeless dip plains, broken only by the valley of the transecting drainage" (73). Due to relatively thin soils, mixed grasses, scattered herbs, and occasional trees and shrubs dominate the Grand Prairie landscape (Hill 1901). In Tarrant County's subtropical climate, rainfall averaged 34 inches per year from 1971-2000 (Ressel 1981; SRCC 2011). Maximum monthly rainfall observations occurred from March through May, and October, while the driest months were January and August (SRCC 2011).

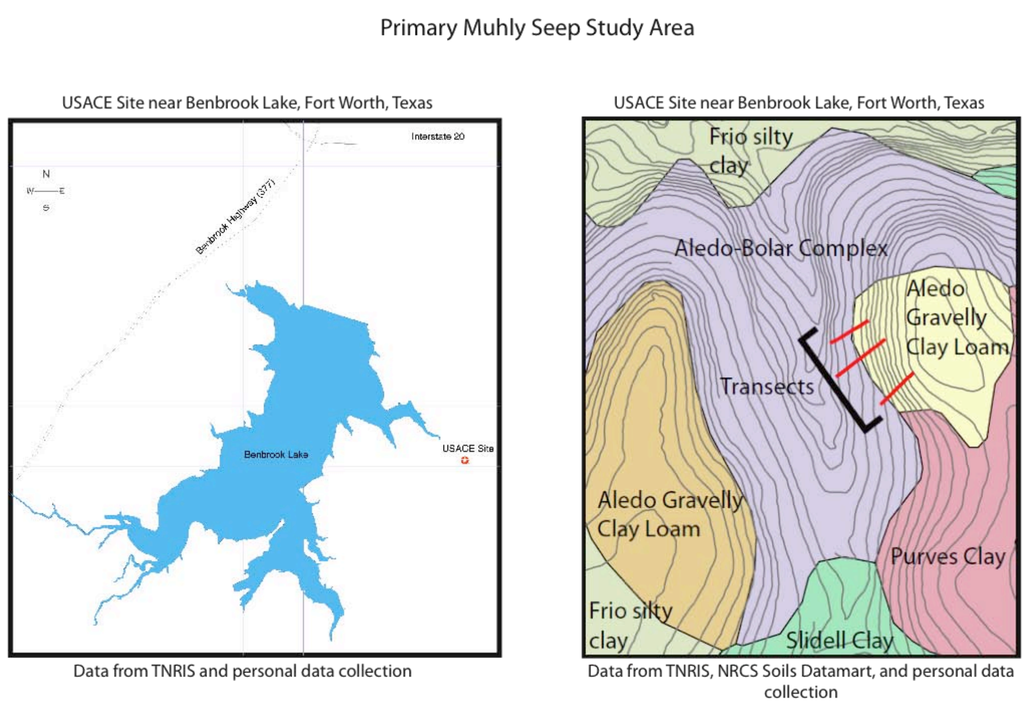


Figure 1. Location of hillslope hollow study site relative to Benbrook Lake (left); Location of study transect within hillslope hollow and associated soils (right)

The portion of the study site selected for hydrologic monitoring is a hillslope containing a Muhly seep and associated barrens system. Primary monitoring occurred along a transect running roughly east to west from a fenceline at the hilltop grading down topographically to an ephemeral stream (Figure 2). The Muhly seep is present at the crest of the transect, while the associated barrens are located along the topographic middle of the transect. A narrow social trail runs through the upper portion of the Muhly seep. The study site was monitored for 8 months, from June 2010 to January 2011. Although the primary objective of fieldwork was to quantify soil water content and water potentials, the associated pedologic and geologic characteristics of the site were also assessed.

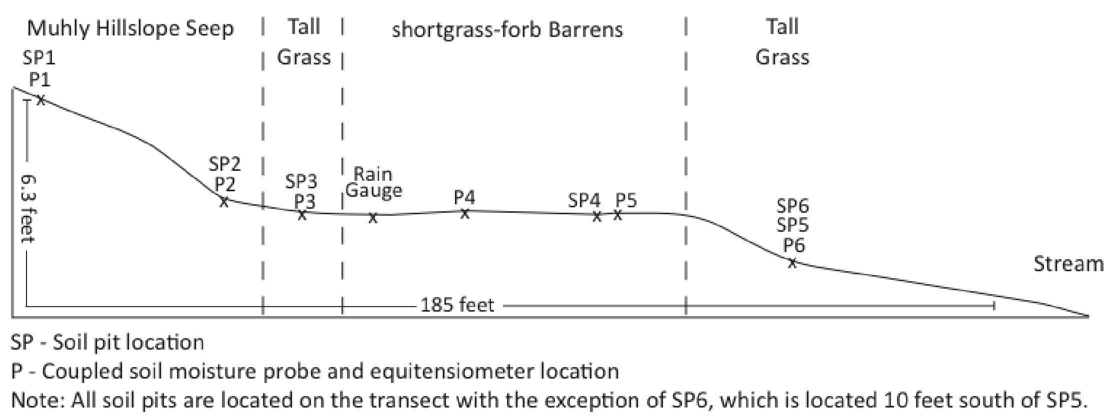


Figure 2. Experimental setup including locations of soil moisture probes, equitensiometers, rain gauge, and soils pits along study site transect east of Benbrook Lake, Tarrant County, Texas

Figure 3. View of experimental setup along study site transect from top of Muhly seep near fenceline. Rain gauge and black boxes used to store loggers are visible.

Soil Moisture Dynamics

To understand the spatial and temporal dynamics of the Muhly seep response, coupled soil moisture probes and equitensiometers were installed at six locations down the transect (Figures 2, 3). Transect locations were selected according to boundaries between the Muhly seep, associated barrens, and tall grass areas based on perceived changes in vegetation, slope characteristics, and hydrology. Due to thin soils, sensors were buried approximately ten inches deep. Delta-T EQ2 equitensiometers were accurate to within ±5% in an optimal range of -100 to -1000 kPa, with slightly less accuracy above -100 kPa. The equitensiometers measured soil matric potential along the lower 2.75 inches of the sensor (approximately 7.25-10 inches below ground at a 30-degree angle) by recording the water content of the surrounding soils and converting to soil matric potential. Delta-T SM200 soil moisture sensors measured volumetric soil moisture content within ±3% in an optimal range of 0-50% soil water volume. The soil moisture probes measured soil water content surrounding two stainless steel rods located at the bottom of the sensor (approximately 10-12 inches below ground at a 30-degree angle). Three Delta-T GP1 compact data loggers recorded data from the soil moisture probes and equitensiometers at 10-minute intervals for the 8-month period. This network monitored six equitensiometers and six soil moisture probes spaced along a 185-foot transect. While the use of coupled soil moisture probes and equitensiometers might seem redundant, the prairie's thin soils and hot climate made it difficult to record data and this method ensured that data could be recorded for the entire 8-month period. For example, the equitensiometers often lost contact with the surrounding soil during dry periods, making the corresponding soil moisture data an important surrogate.

Rainfall

A Texas Electronics TE525 tipping bucket rain gauge measured rainfall at 10-minute intervals at a central location along the transect (Figures 2, 3). Since rainfall data from the tipping bucket rain gauge was only available after September 15, 2010 due to technical difficulties, additional daily rainfall data supplemented the record. Data from four nearby rain gauges were compared to the study site rainfall record. Linear regression analysis of the four gauges indicated KTXFORTW58, located approximately three miles southeast of the study site, correlated best to the site data with an R-squared of 0.951 (Figure 4). Therefore, rainfall records from KTXFORTW58 substituted for the missing study site rainfall data.

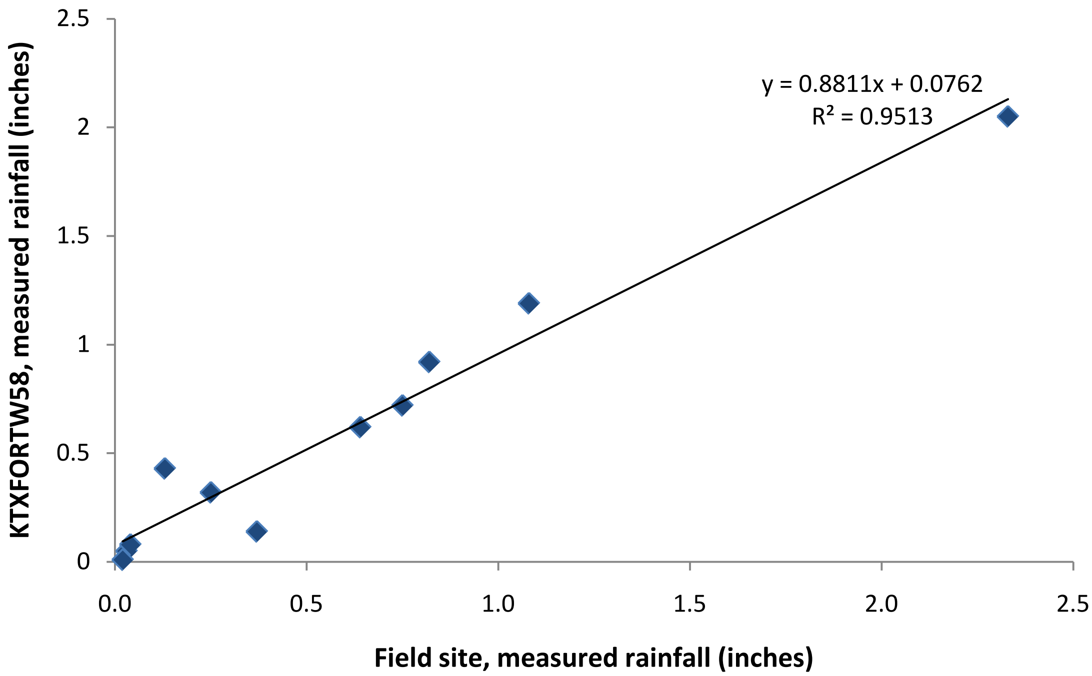


Figure 4. Linear regression between rainfall measured at field site and at KTXFORTW58

Pedology, Geology, and Topography

To verify soil map data, six soil pits were dug along the transect at perceived changes in vegetation and hydrology (Figure 2). At each soil pit, the following parameters were identified: horizon designation, horizon depth, textural class, and color. Corresponding lithology for each soil pit was also sampled and identified, along with any geologic contacts discovered during excavation. With the exception of the thin (generally 1” or less) A1 horizons, samples from horizons were sent to the Agrilife Extension labs at Texas A&M University for additional analysis. The hillslope hollow topography was surveyed using a Leica laser sighted total station.

Results and Discussion

Data generated for this study include rainfall, volumetric soil water content and soil water potential, topography, and soil and geologic descriptions. Data collection began on May 1, 2010 and continued until January 31, 2011.

Soil Moisture Regimes

One objective of the study was to describe soil moisture regimes for Muhly seeps and associated barrens that might be applicable to other Grand Prairie Muhly seeps. A visual assessment of 8 months of soil moisture and equitensiometer data was conducted. Due to the large range of possible values for the equitensiometers (0 to -1000 kPa) and variable rainfall, it was difficult to establish a moisture regime based on equitensiometer data with any statistical significance (Figure 5). Additionally, within certain ranges of suction, equitensiometers often lose contact with the surrounding soil until they “recharge” (Marshall et. al 1999, 64), making equitensiometer data most useful during storm conditions.

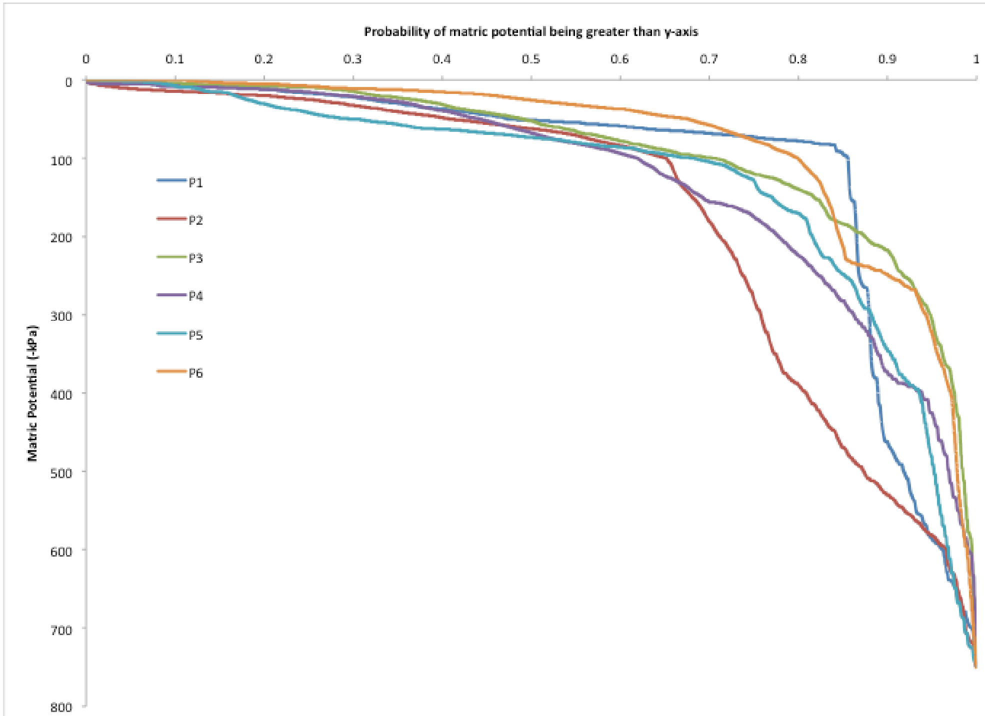


Figure 5. Analysis of 8-months of equitensiometer data at six ports along study site transect near Benbrook Lake, Fort Worth, Texas

The relatively large spread in matric potential at P2 is likely due to extreme moisture regimes experienced at that location (Figure 5). During dry periods, P2, located at the clayey bottom of the Muhly seep, becomes completely desiccated, but is also one of the wettest areas following storms. At P2, water potential was less than -250 kPa 73% of the time, while the location remained at field capacity 31% of the time (Appendix A). Additionally, a generally decreasing trend in matric potential is evident from P3 to P5, with an increase in matric potential at P6. At P3, water potential was less than -250 kPa 10% of the time, while the area remained at field capacity less than 1% of the time. In contrast, at P4 and P5, on the barrens, water potential was less than -250 kPa less than 1% of the time, while the areas remained at field capacity for less than 1% of the time. At the bottom of the slope, P6, water potential increased, remaining at -250 kPa 14% of the time, but below field capacity less than 1% of the time.

Analysis of soil moisture data along the transect revealed interesting trends (Figure 6). Long-term soil moisture readings for the stations at the top, middle, and bottom of the slope seeps (P1-P3) revealed relatively similar soil moisture values, with means ranging from 28-29%. The ports located at the top (P4) and bottom (P5) of the barrens transect exhibited the lowest soil moisture, with mean soil moisture values of 21.7% and 17.1%, respectively. At the lowest station on the transect (P6), located directly above the stream, soil moisture increased to approximately the same range as the station at the top of the barrens, likely due to saturated wedge migration upward from the stream. Additionally, the same trend observed in the equitensiometer data, with values generally decreasing from P3 to P5, then increasing at P6, is also evident in soil moisture data (Figure 6). These soil moisture ranges indicate that the long-term difference in soil moisture between the slope seeps and associated barrens is visually significant. Furthermore, a comparison of the study site barrens soil moisture range to values obtained from a simulated Grand Prairie barrens environment in living roof boxes show that average soil moisture values correspond between studies (Williams 2006).

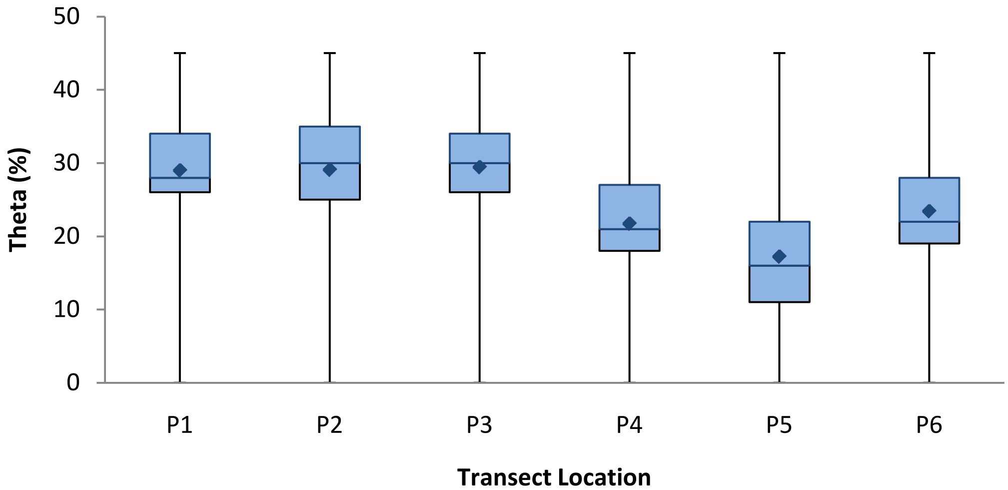


Figure 6. Analysis of 8-months of soil moisture data at six ports along study site transect near Benbrook Lake, Fort Worth, Texas. Edges of the blue boxes indicate the 25-75% range, the center line indicates the median value, and the diamond indicates the mean value.

Rainfall

Historic rainfall data was compared to rainfall data recorded over the 8-month period at the study site (Table 1). While 8-month rainfall totals for climate data versus the study site data were similar (20.95 and 18.80, respectively), an unusually large amount of rainfall fell at the study site during September 2010 (7.80 inches). When the September study site rainfall is excluded from the 8-month total, it becomes apparent that the study period was quite dry relative to historic climate.

Table 1. Comparison of Southern Regional Climate Center (SRCC) historic climate data for Tarrant County with study site rainfall measurements

	Rainfall (inches)	
Month	**SRCC Historic Data**	**Study Site**
January	1.9	1.20
February	2.37	n/a
March	3.06	n/a
April	3.2	n/a
May	5.15	n/a
June	3.23	3.00
July	2.12	2.70
August	2.03	0.80
September	2.42	7.80
October	4.11	0.80
November	2.57	1.20
December	2.57	1.30
Study Total	20.95	18.80
Year Total	34.73	n/a

Storms with a total volume of at least 0.5 inches per storm event were selected for further analysis. If there was at least a six-hour gap between storms, or if the storm period straddled more than one day, the storms were considered separate from one another. Storm intensity calculations were performed for each of the twelve storms that fit these criteria within the 8-month period (Table 2). Comparison of calculations to storm intensity maps from the USACE revealed that none of the storms exceeded 2, 10, or 100 year intensities for the study area (Dunne 1978). Maximum 24-hour rainfall intensities were observed during the September 7th, 8th, and 25th storms. While sub-24 hour rainfall data was not available for the September 7th and 8th storms, sub-24 hour calculations for the September 25th storm exceeded rainfall intensities observed during any of other storms (Table 2).

Table 2. Storm intensity calculations for storms exceeding 0.5 inches daily total over 8-month period. Storms followed by an asterisk indicate snowfall events.

	Max Intensity (inches/hour)					Storm Total
Date	**10-minute**	**30-minute**	**60-minute**	**120-minute**	**24-hour**	**(Inches)**
June 28, 2010	n/a	n/a	n/a	n/a	1.03	1.03
June 29, 2010	n/a	n/a	n/a	n/a	0.79	0.79
June 30, 2010	n/a	n/a	n/a	n/a	0.74	0.74
July 6, 2010	n/a	n/a	n/a	n/a	0.73	0.73
July 9, 2010	n/a	n/a	n/a	n/a	0.85	0.85
September 7, 2010	n/a	n/a	n/a	n/a	2.40	2.40
September 8, 2010	n/a	n/a	n/a	n/a	2.48	2.48
September 25, 2010	1.38	0.90	0.90	0.72	2.33	2.33
October 23, 2010	1.02	0.64	0.42	0.25	0.64	0.64
November 2, 2010	0.24	0.18	0.10	0.07	0.82	0.82
December 24, 2010*	0.42	0.24	0.16	0.08	0.75	0.75
January 9, 2011*	0.24	0.20	0.16	0.15	1.08	1.08

In addition to analysis of the twelve storm events, the antecedent rainfall index was calculated for the 8-month period. The antecedent moisture content (AMC) over the eight-month period was calculated by taking the average soil moisture among all six stations along the study area transect (θ=24.96). The resulting antecedent precipitation index (API) plot shows the average behavior of the field site soils in response to rainfall, with the greatest rainfall and highest average soil moisture content in June, July, and September 2010 (Figure 7).

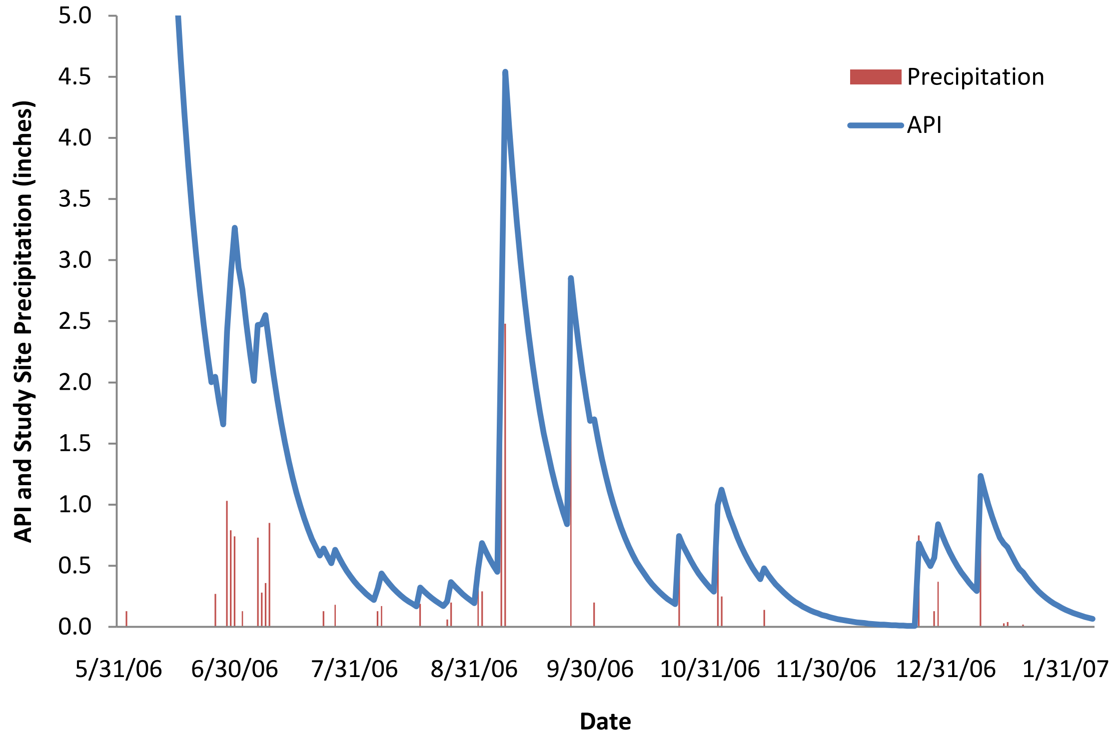


Figure 7. Rainfall record and API trends for study site over 8-month period

Muhly seep response to individual storm events was also analyzed using soil moisture potential and rainfall measurements. Due to infrequency of storms during the 8-month period and lack of 15-minute rainfall data for some of the storms due to equipment malfunction, it was impossible to select a handful of storms of similar storm size and intensity. While the October 23, 2010 and November 2, 2010 storms were of similar magnitude, storm intensity and duration significantly differed. The December 24, 2010 and January 9, 2011 storms yielded several inches of snow, creating an entirely different hydrologic environment. Therefore, Muhly seep response during two storms of significantly different intensities, but with the same type of precipitation, was assessed: a large storm event on September 25, 2010 and a relatively small storm event on

October 23, 2010 (Figure 8). Further justification for comparison of the two storms includes typical storm volume for the area. For instance, while the October 23, 2010 storm seems inconsequential compared to other storms during the 8-month period, it is important to note that sub-inch storms account for nearly half (47.2%) of the rainfall observed in the Tarrant County area between 1949 and 2010. Storm events between one and two inches account for 32.47 percent of all storms between 1949 and 2010 (Williams 2006, 34). Therefore, while the September 25, 2010 storm produces the greatest hydrologic response, storms of similar magnitude have been relatively uncommon to the study site.

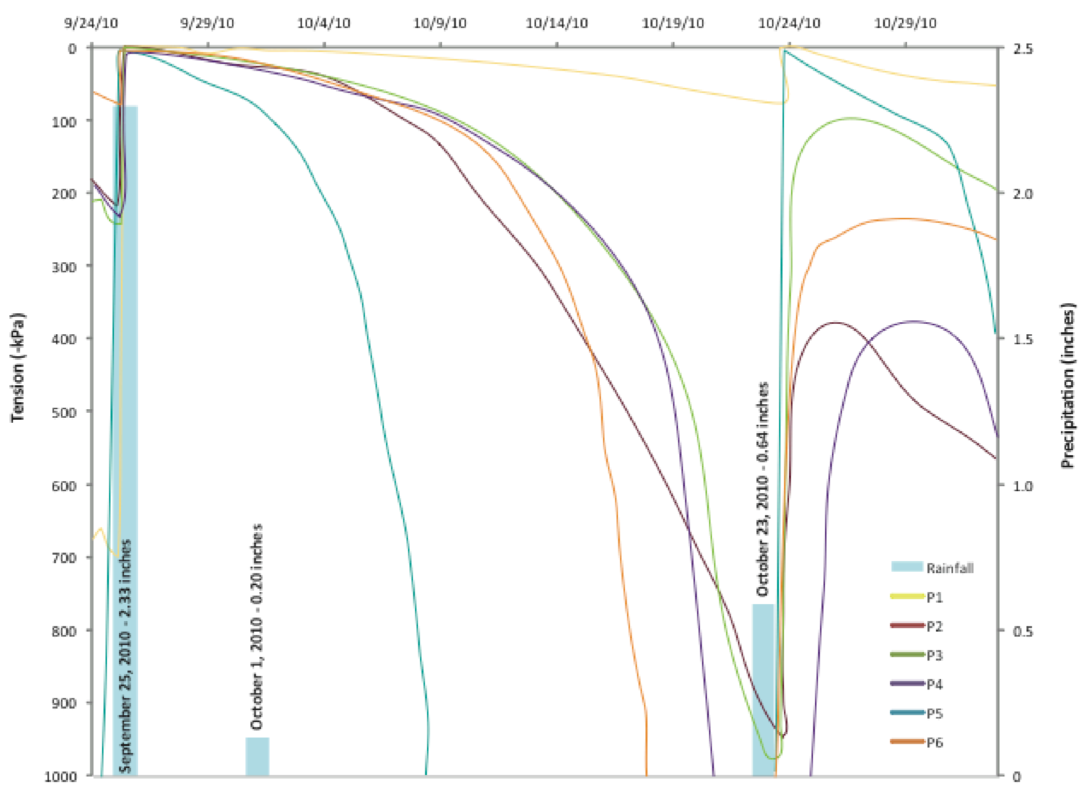


Figure 8. Muhly seep response between September 24, 2010 and November 1, 2010, showing individual rainfall events and equitensiometer readings

During the September 25, 2010 storm, rainfall occurred between 3:00 AM and 12:40 PM, with a storm total of 2.33 inches and maximum 10-minute rainfall intensity of 1.38 inches/hour recorded at 4:10 AM, and again at 9:10 AM (Table 2). Most rainfall was recorded during the last few hours of the storm. Due to storms earlier in the month (September 7 and September 8), the API for the study site was relatively high, at 0.93 inches the day prior to the storm (Figure 7). P5 was the driest location prior to the storm, followed by P1, P2, and P4. In summary, the wettest portion of the transect was the area closest to the ephemeral stream (P6), while the rest of the transect, particularly the lower barrens (P5), was relatively dry. Response time for the locations along the transect was also assessed (Table 3). For example, the time to first increase was the period from the beginning of the storm to the first increase in soil matric potential. Time to saturation, first decrease, and halfway to wilting point were also calculated from the beginning of the storm. With the exception of a 3.2-hour response time at P4, located at the top of the barrens, all of the equitensiometers responded to rainfall in a little over an hour. Only two locations, P1 and P5, reached complete saturation (0 kPa) during the storm. With the exception of P1 and P5, all of the locations dried out in approximately the same time period (58.2-61.7 days) and trended halfway to wilting point (-750 kPa) within 21-26 days. For example, P5 reached halfway to wilting point in only 11 days. Soil tension at P1, the uppermost location at the top of the slope seep, stayed above halfway to wilting point until the October 23rd storm. Soil moisture dynamics at P5, the driest part of the transect located on the lower barrens, also differed from the rest of the transect. P5 began to dry out almost a day before the other locations and reached wilting point approximately two weeks before the other locations (Table 3).

During the October 23, 2010 storm, rainfall occurred between 12:50 PM and 4:30 PM, with a storm total of 0.64 inches and a maximum 10-minute rainfall intensity of 1.02 inches/hour occurring at the beginning of the storm (Table 2, 3). Due to minimal rainfall since the September 25 storm, the API for the study site was relatively low, at 0.21 inches the day prior to the storm (Figure 7). Pre-storm moisture status at the individual transect locations was highest at P1, high antecedent moisture from the September 25 storm (Table 3). P5 was the driest location prior to the storm, followed by P6, P4, and P3. In summary, the wettest portion of the transect was the Muhly slope seep (P1-P3), while the rest of the transect, particularly the lower barrens (P5), was relatively dry. All of the equitensiometers responded to rainfall within 1.7-3.7 hours, with the exception of P4, which was out of range for the duration of the storm. On October 25, two days after the storm, field observations noted that the sensor at P4 had been removed from the ground, likely due to human activity in the area. The sensor was reinstalled on October 25. Similar to the September 25 storm, P1 and P5 responded several hours before the other locations. None of the equitensiometers recorded saturation conditions during the storm or recorded measurements half way to wilting point before the next storm occurred. Similar to the September 25 storm, the responses at P1 and P5 differed from the rest of the slope. P1 and P5 responded to rainfall more quickly than the other locations, and also began to dry out sooner by approximately 24 hours than the other locations. This response is likely due to increased moisture in the ephemeral stream migrating upslope and increasing soil moisture at the lowest transect location. The week previous to the October 23 storm, trace moisture in the ephemeral stream below the transect was observed during fieldwork, which had previously been dry during September.

Despite differing magnitudes, comparison between the September 25 and October 23 storms reveals some interesting patterns. Most strikingly, the barrens soil responds differently from any other transect location. P5, located at the bottom, driest portion of the barrens, displayed one of the quickest responses to rainfall, was one of the only locations that completely saturated, and dried out and trended toward wilting point quicker than any of the other locations. While responses of soils throughout the rest of the transect were fairly similar for the September 25 storm, the same trends were not observed for the smaller October 23 storm. This could be due to a number of factors. The high September API value, along with the large September 25 storm volume could have diluted the response of the different areas of the seeps. During the smaller October 23 storm, lower storm volume allowed topography and pooling of water along concave portions of the transect to affect response. Additionally, with smaller storm volume and duration, water may have taken longer to filter through the fractured limestone strata into the marls, causing the areas with exposed limestone, such as above P1, to respond well before the lower portions of the transect (P2 and P3). Noy-Meir (1974) made this same observation, concluding that upslope impervious surfaces concentrate moisture.

Table 3. Soil tension analysis for storm on September 25, 2010 and October 23, 2010. Locations with an asterisk indicate that the equitensiometers were out of range prior to the "1st Increase" value.

September 25, 2010			Storm Start	3:00 AM
			Storm End	12:40 PM
			Storm Duration	9.6 hours
	Hours to…			**Days to 1/2 Wilting Point (-750 kPa)**
Location	**1st Increase**	**Saturation (0 kPa)**	**1st Decrease**	
P1	1.5	6.8	59.5	n/a
P2	1.6	n/a	60.5	26
P3	1.3	n/a	59.0	25
P4	3.2	n/a	58.2	24
P5*	1.7	6.2	33.8	11
P6	1.3	n/a	61.7	21
October 23, 2010			Storm Start	12:50 PM
			Storm End	4:30 PM
			Storm Duration	3.6 hours
	Hours to…			**Days to 1/2 Wilting Point (-750 kPa)**
Location	**1st Increase**	**Saturation (0 kPa)**	**1st Decrease**	
P1	1.7	n/a	25.0	n/a
P2	3.7	n/a	53.3	n/a
P3	3.2	n/a	72.5	n/a
P4*	n/a	n/a	n/a	n/a
P5*	0.8	n/a	22.2	n/a
P6*	2.5	n/a	100.8	n/a

Pedology and Geology

Table 4 displays results from field and lab soils analysis, and Figure 9 displays photographs of soil pits with clearly marked horizons. Soil field results predicted that all of the soil pits along the transect had a thin (0"-3") A1 horizon, grading from loamy clay to sandy loam to silty clay loam from high to low elevation. Despite slight differences perceived during field analysis, laboratory results indicated that soils were fairly consistent clay loams with occasional sandy clay loams. Additionally, the soils had an extremely high carbonate concentration (ranging from 33191-46847 ppm) as a result of the carbonate-rich parent material.

The primary contrast in soil profiles, noted in both the field and laboratory analysis, was the presence of 2.5Y series clays (marls) at depths ranging from 7-11" in SP1-East, SP1-West, and SP3. At SP1, located at the crest of the transect, limestone on the east side of the pit abruptly transitions into marl on the west side of the pit. The discovery of in-place limestone bedding exposed at the surface several feet upslope from the beginning of the transect, as well as slightly deeper marls at SP3, reinforced the presence of the contact discovered at SP1. Depth to bedrock varied significantly along the transect. Construction of the shallowest soils pits occurred over the barrens portion of the transect (SP4-East, SP4-West, and SP5), while construction of the deepest pits occurred over the slope seep (SP1-3). At SP6, located at the same elevation as SP5, but 10 feet south of the transect, a big bluestem patch corresponded with deeper soils.

The discovery of the geologic/pedologic contact at SP1 and variable depth to bedrock along the transect was critical to identifying areas where seeps outcropped along the transect. The contacts between soil and underlying materials are likely paralithic contacts, rather than lithic. In contrast to lithics, paralithics "are relatively unaltered materials [with] extremely weakly cemented to moderately cemented ruture-resistance class" (Soil Survey Staff 2001, 26). Paralithic contacts "have no cracks or the spacing of cracks that roots can enter is 10 cm or more" (Soil Survey Staff 2001, 26). Additionally, paralithics often occur in association with shaley or marly layers, like the interbedded marls (2.5Y series) along the transect.

Lab analysis suggests that all transect soils, excluding SP1 and SP4 on the barrens, are mollisols. Mollisols are mineral soils with relatively thick, dark surface horizons and high organic content that develop under prairie vegetation in subhumid climates with carbonate rich parent materials (Thompson and Bell, 2001). Additionally, mollisols in the wettest potions of hillslopes have greater thicknesses and decreased Munsell value and chroma. Study site soils analysis confirms this trend; soils associated with the lower slope seep (Pits 2 and 3) and the area within a dense patch of the tall grass *Andropogon geradii* (Pit 6) have greater thicknesses and decreased Munsell value and chroma relative to other soils along the transect. The soils at SP1, SP4, and SP5 are likely inceptisols, “mineral soils with minimal horizon development and parent material differentiation that are most frequently found on flood plains or terraces” (Watts et. al 2001, 320).

A number of factors, such as high organic content and mixing by soil organisms, make it difficult to identify mollisols as hydric soils, one of the parameters necessary for wetlands delineation. While the soils at Pits 1-East, 1-West, 2, 3, and 6 display some of the characteristics of hydric soils, such as the presence of some oxidized root channels and yellow soil colors (2.5Y) below the upper dark matrix, other hydric soil field indicators for mollisols are absent. Due to the hyperseasonal nature of the seeps, it is possible that soils dry out during part of the year and reoxygenate, then become anaerobic during wetter portions of the year. Therefore, hydric properties may be impossible to observe year-round.

Table 4. Field description and laboratory analysis for six soil pits along study site transect (continued on page 26)

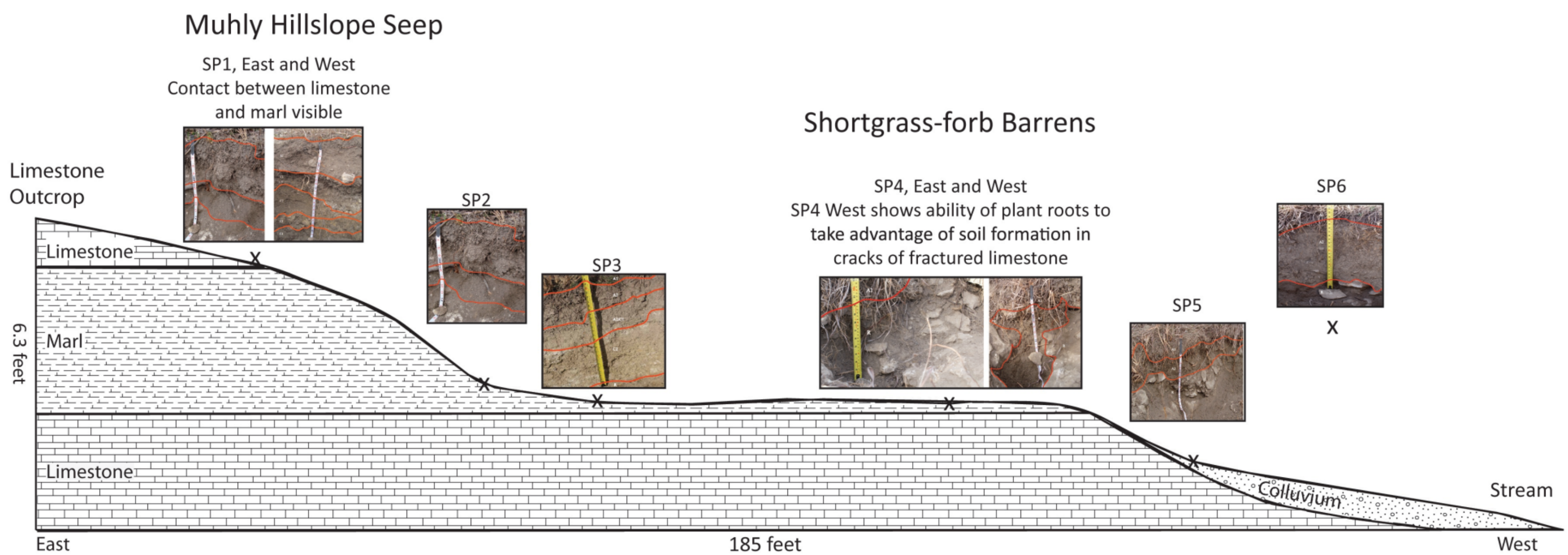
	Field Analysis					Lab Analysis						
Soil Pit	**Horizon**	**Depth**	**Color (dry)**	**Rock Fragment Size and %**	**Textural Class**	**pH**	**Calcium (ppm)**	**Sand (%)**	**Silt (%)**	**Clay (%)**	**Textural Class**	**Organics (%)**
1-East	A1	0"-1"	10YR 3/2	Few fragments	loamy clay	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	A2	1"-7"	10YR 3/2	Abundant fragments	silty clay loam to clay loam	8	39675	36	30	34	clay loam	4.63
	C	7"-9"	2.5Y 5/2	a	silt loam to silty clay loam	8.1	44815	40	22	38	clay loam	3.16
	R[1]	9"+	2.5Y 5/2		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1-West	A1	0"-1"	10YR 3/2	Few fragments	loamy clay	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	A2	1"-8"	10YR 3/2	Abundant fragments	silty clay loam to clay loam	8	44620	45	27	28	clay loam	1.76
	C1	8"-11"	2.5Y 5/2	a	silt loam to silty clay loam	8.1	45824	44	20	36	clay loam	0.97
	C2	11"-16"	2.5Y 5/3	b	silt clay loam	7.9	45294	41	21	38	clay loam	2.01
	C3	16"-18"	2.5Y 6/3	c	clay loam	7.9	44916	36	24	40	clay	1.84
	C4	18"-27"+	2.5Y 8/3	d	silt loam to loam	7.9	44703	28	30	42	clay	1.02
2	A1	0"-1"	10YR 4/2	Few fragments	loamy clay	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	A2	1"-13"	10YR 4/2	Few fragments	clay	7.8	41546	33	33	34	clay loam	2.93
	C1	13"-24"	10YR 5/6	Abundant fragments	clay	8.1	46847	29	35	36	clay loam	2.06
	C2	24"+	10YR 5/6		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
3	A1	0"-1"	10YR 3/2	Few fragments	loamy clay	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	A2	1"-8"	10YR 3/2	Abundant fragments	clay	8.1	43268	43	25	32	clay loam	2.53
	A2/C1	8"-11"	10YR 4/2	Few fragments	clay	8.2	45122	43	25	32	clay loam	2.14
	C2	11"-16"	2.5Y 6/4	Few fragments	loamy clay to clay	8.1	45956	29	27	44	clay	4.11
	R[1]	16"-18"+	2.5Y 5/4	Few fragments	loamy clay	n/a	n/a	n/a	n/a	n/a	n/a	n/a
4-East	A1	0"-3"	10YR 4/3	Few fragments	sandy loam	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	R[1]	3"+	10YR 4/3	Abundant fragments	sandy clay loam	8.1	31991	44	24	32	clay loam	3.94
4-West	A1	0"-3"	10YR 4/3	Few fragments	sandy loam	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	A2	3"-3.5"	10YR 4/3	a	sandy loam	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	C	3.5"+	10YR 4/3	Abundant fragments	sandy clay loam	8	43689	47	22	31	sandy clay loam	3.57

Continuation of Table 4. Field description and laboratory analysis for six soil pits along study site transect

Soil Pit	Field Analysis					Lab Analysis						
	Horizon	Depth	Color (dry)	Rock Fragment Size and %	Textural Class	pH	Calcium (ppm)	Sand (%)	Silt (%)	Clay (%)	Textural Class	Organics (%)
5	A1	0"-2"	10YR 3/2	Abundant fragments	silty clay loam	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	A2	2"-10"	10YR 3/2	Few fragments	silty clay	8.1	31716	39	26	35	clay loam	4.81
	R[1]	10"+	10YR 3/2		silty loam	8.1	44850	45	22	33	clay loam	2.99
6	A1	0"-1.5"	10YR 3/2	a	silty clay loam	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	A2	1.5"-17"	10YR 3/2	b	silty clay	8.2	35139	37	24	39	clay loam	3.47
	R[1]	17"+	10YR 4/2	c	silty loam	7.8	44131	43	24	33	clay loam	2.65

1 – Hard limestone

Rock fragment size and %: a=~25-30% gravel, 10% cobble; b=~20% micritic limestone cobbles, 5-10% gravel; c=>5% gravel present; d=few gravel pieces present



Note: All soil pits are located on the transect with the exception of SP6, which is located 10 feet south of SP5.

Figure 9. Soil pit locations along study site transect with photos of soil horizons

Conclusions

Analysis of Muhly seep response to rainfall confirms previous hypotheses (Burgess 2010) regarding the mechanisms behind Muhly seep moisture dynamics. Study results confirm that fractured limestone upper slope seeps and barrens environment should respond first to rainfall. As water filters through the fractured limestone at the top of the Muhly seeps, the lower clay portions of the slope will become saturated. These lower portions of the seeps appear to stay saturated as long, or longer than of the surrounding environment. Larger storm events, such as the September 25, 2010 storm, combined with high API dilute the response of the Muhly seeps. However, as mentioned previously, large storm events (greater than 2 inches in volume) are not the norm for the Tarrant County region. The small scale October 23, 2010 storm should represent the normal response for Muhly seep systems.

Associated fieldwork included monthly soil moisture measurements and vegetative collections from two other Grand Prairie sites over the same 8-month period as this study. Future research could compare the primary study site with other seep sites to test the observed pattern of Muhly seep soil moisture regimes. In addition to the possible extension of the USACE Muhly seep science to other Grand Prairie sites, a number of possible applications exist for the ecosystem-scale analysis of Muhly seeps. Although current research does not examine the ability of the Muhly seeps to filter water, the seeps' geographic locations in depressions or hollows could make them useful models for biofiltration swales (Jurries 2003) or grey water filtration systems (Al-

Jayyousi 2003). Also, due to their hyperseasonal nature, Muhly seeps could serve as models for native green roofs, particularly in climates with erratic rainfall.

The hydrologic and ecologic significance of Muhly seeps to the Grand Prairie system makes them a vital area of research. This study focuses on the hydrology of Muhly seeps during low flow and storm conditions, and demonstrates that associated pedology and geology are critical for an understanding of seep mechanics. Results suggest the study site Muhly seep represents an inverse of the traditional saturated wedge theory resulting from the interbedded limestone and marl geology of the Grand Prairie. At the study site, the variable source area is present at the wettest, upper portion of the hillslope at the Muhly seep. The Muhly seep is hydrologically disconnected from the lower slope and ephemeral stream by the intervening barrens over limestone. Results suggest that when the ephemeral stream is inactive, minimizing the impact of saturated wedges forming from the streambed, the Muhly seeps may be the most important source of moisture on the hillslopes. Since the Grand Prairie system and similar geology are quite expansive, the hydrologic response observed in Muhly seep systems could be applicable on a larger scale. Soil moisture results are consistent with the vegetation patterns described by Jue (2011). Therefore, vegetation structure and composition seems to be a reliable predictor of soil moisture regimes, and this study has revealed ecological structuring mechanisms more accurately than previous work.

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ABSTRACT

SOIL MOISTURE DYNAMICS OF MUHLY SEEPS IN A HILLSLOPE HOLLOW DURING LOW FLOW AND STORM CONDITIONS

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Groundwater seeps are important hydrological and ecological features of many landscapes. Research on hyperseasonal Muhly hillslope seeps, dominated by Seep Muhly grass (*Muhlenbergia reverchonii*), has been limited. Muhly seeps result from interbedded Cretaceous limestone and marl geology of the Fredericksburg and Washita Groups of the Grand Prairie Ecoregion and are found on middle to lower slopes, often with an associated barrens environment. Results indicate that geologically controlled Muhly seeps are hydrologically disconnected from the rest of the hillslope, with the wettest portions of the hillslope at the Muhly seeps. The mechanics of these systems present a departure from traditional VSA and saturated wedge hillslope theories. Due to the extent of comparable geology within the Grand Prairie, results from this study could apply across a sizeable area, representing a large-scale deviation from traditional hillslope hollow mechanisms.