BASELINE HYDROLOGY FOR A LONG-TERM STREAM MONITORING PROGRAM: A FIRST STEP TOWARD SUSTAINABLE WATER MANAGEMENT AT THE TEXAS CHRISTIAN UNIVERSITY TROPICAL RESEARCH STATION

by

ABBY SCHLIPMANN

Bachelor of Science, 2004
University of Illinois Urbana-Champaign
Champaign-Urbana, Illinois

Submitted to the Graduate Faculty of the
College of Science and Engineering
Texas Christian University
in partial fulfillment of the requirements
for the degree of
Masters of Science

August 2009

ACKNOWLEDGEMENTS

Many thanks to my family for their love and support; especially my parents who, growing up, would not stand for less than my best, so thank you for setting such high standards for me.

Thank you to my thesis advisor, Dr. Michael Slattery, for his guidance, encouragement, and understanding, and also thank you for all the unforgettable opportunities. To the other members of my thesis committee, Dr. Tony Burgess and Becky Richards, thank you not only for your assistance on my thesis but also for a truly unique and invaluable education at TCU. To Morgan Dezendorf, my Costa Rica companion and trusted friend; I could not have done this without you.

Thank you, Gustavo Orozco, for having a life-long dream to one day run a tropical research station for an American University and for being such a gracious and generous host.

I am eternally grateful to the experts who were so ever patient and helpful; Dr. Allison Davis-Stamatis for her knowledge of aquatic invertebrates and the GIS geniuses Tamie Morgan and Jay Nash.

Dave Williams, thank you for all your hard work at the research station and for showing me the ways of cartography. Thank you also to Tyler Smith, Leslie Martin, and Richard Arthur Bill for your diligence in aquatic insect and GPS data collecting. To the Costa Rica ’09 students; thank you for your data contribution.

I would like to thank University of Illinois for a well-rounded, fundamental undergraduate experience and Texas Christian University for an exceptional graduate experience.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS II

TABLE OF CONTENTS III

LIST OF FIGURES IV

LIST OF TABLES V

INTRODUCTION AND BACKGROUND 1

STUDY SITES AND METHODS 16

RESULTS & DISCUSSION 22

CONCLUSION 46

APPENDIX 49

REFERENCES 52

VITA

ABSTRACT

LIST OF FIGURES

FIGURE 1: MAP DEPICTING THE RESEARCH STATION LOCATION 4

FIGURE 2: MAP OF THE TCU TROPICAL RESEARCH STATION........ 6

FIGURE 3: COSTA RICA SOILS 9

FIGURE 4: WATER SOURCE FOR THE HOUSES AND CABINS 10

FIGURE 5: CIRCULATION TANK........ 11

FIGURE 6: TWO HOLDING CISTERNS 11

FIGURE 7: TANK SENDS WATER TO THE CABINS BY FORCE OF GRAVITY. 11

FIGURE 8: MAP OF THE PROPERTY'S FRESH WATER SUPPLY 12

FIGURE 9: TAKING CROSS-SECTIONAL DATA AT STUDY SITE 1 17

FIGURE 10: TAKING CROSS-SECTIONAL DATA AT STUDY SITE 2 17

FIGURE 11: CROSS-SECTION OF THE STREAM AT STUDY SITE 1 FROM JANUARY 3, 2009 22

FIGURE 12: CROSS-SECTION OF THE STREAM AT STUDY SITE 2 FROM JANUARY 3, 2009 24

FIGURE 13: UNRESTRICTED ACCESS OF CATTLE TO THE STREAMS........ 25

FIGURE 14: DRAINAGE BASIN OF THE RESEARCH STATION........ 26

FIGURE 15: DIGITAL ELEVATION MODEL........ 27

FIGURE 16: STAGE AND RAINFALL PLOTTED OVER TIME 28

FIGURE 17: VELOCITY RECORDED AT EACH STUDY SITE PLOTTED AGAINST STAGE........ 31

FIGURE 18: DRAINAGE BASIN AREA AND PEAK LAG TIME 32

FIGURE 19: THE LIVESTOCK ARE CREATING DEPRESSIONS THROUGHOUT THE LANDSCAPE 34

FIGURE 20: CONDUCTIVITY PLOTTED WITH RAINFALL AT STUDY SITE 1 35

FIGURE 21: CONDUCTIVITY PLOTTED WITH RAINFALL AT STUDY SITE 2 36

FIGURE 22: DISSOLVED OXYGEN AND STAGE PLOTTED OVER TIME AT STUDY SITE 1........ 37

FIGURE 23: DISSOLVED OXYGEN AND STAGE PLOTTED OVER TIME AT STUDY SITE 2........ 39

FIGURE 24: HYSTERESIS: STUDY SITE 1........ 40

LIST OF TABLES

TABLE 1: FRAMEWORK FOR A SUSTAINABLE WATER MANAGEMENT PLAN 2

TABLE 2: CLASSIFICATION OF POTABILITY BASED ON CONDUCTIVITY (HART, 2002) 18

TABLE 3: DATA LOGGING DATES AND THEIR HISTORICAL AVERAGE CLIMATE DATA 19

TABLE 4: DURING TIME OF STUDY, THERE WERE 4 RAINFALL EVENTS THAT SIGNIFICANTLY RAISED STREAM STAGE AT STUDY SITE 1 (SEE FIGURE 16). 29

TABLE 5: DURING TIME OF STUDY, THERE WERE 10 RAINFALL EVENTS THAT SIGNIFICANTLY RAISED STREAM STAGE AT STUDY SITE 2 (SEE FIGURE 16). 29

TABLE 6: RESULTS FROM AQUATIC MACROINVERTEBRATES SAMPLING 41

TABLE 7: RESULTS OF THE SIMPSON'S INDEX EQUATION (1949) AND AVERAGE SCORE PER TAXON (ASPT) (ROSENBERG, 1993) 42

TABLE 8: POSSIBLE RESEARCH PROJECTS 45

INTRODUCTION AND BACKGROUND

An awareness of ignorance is the first step in learning, for until we become aware that we do not know something, we are probably unaware that the opportunity for the acquisition of learning even exists.

Darryl Cole-Christensen, 1997

(referring to the complexity of life relationships within the rain forest of Costa Rica)

Indeed, as Cole-Christensen (1997) states, it is virtually impossible to fully understand the intricacies of ecological interactions in a place as dynamic as the Costa Rica rain forest. With Texas Christian University's (TCU's) establishment of a research station in the Costa Rica cloud forest in 2007, a new opportunity for the ‘acquisition of learning’ emerged for TCU student and faculty researchers from different educational backgrounds. The TCU Institute for Environmental Studies laid out ambitious educational goals. One aspiration for the TCU Tropical Research Station is to be sustainable, which must include a sustainable water management program. People at the station rely on water from the local streams because there is no municipal water supply. Sustainable water use can be defined as “the use of water that supports the ability of human society to endure and flourish into the indefinite future without undermining the integrity of the hydrological cycle or the ecological systems that depend on it” (Gleick et al., 1995, p. 23). It is imperative that TCU Tropical Research Station researchers begin to understand the local life relationships to which Cole-Christensen refers to realize the impact management decisions may have on local streams and their organisms. With such understanding, they can become responsible stewards of the property. These decisions can be made more wisely if a monitoring system has already provided baseline data. A monitoring system is the foundation for a sustainable water management plan.

A sustainable water management plan should be well thought-out and may take a year or more to develop (Richter et al., 2003). Its main purpose is to prevent over-use and abuse of a watershed. The most successful sustainable water management plans are multi-faceted and contain components that this project is currently unable to produce, such as how many students will occupy the research station at a given time. One example of the components in a sustainable water management plan is described in Table 1. This project, a first step in sustainable water management, will address several of these steps (Table 1).

Step #	**Step Description**	**Step Addressed in this Project?**
Step 1	Estimate Ecosystem Flow Requirements	Partial. No estimate was made. A baseline sample of macroinvertebrates was taken to aide in estimation.
Step 2	Determine Influence of Human Activities	No. Current influence determined as minimal, but this must be re-determined for the sustainable water management plan once researchers begin spending substantial amounts of time at the research station.
Step 3	Identify Areas of Potential Incompatibility (between human demands and ecological requirements)	No. Steps 1 and 2 must first be determined.
Step 4	Foster Collaborative Dialogue to Search For Solutions	Yes. This project aims to initiate a dialogue by being made available to every person visiting the research station.
Step 5	Conduct Management Experiments to Resolve Uncertainty	Yes. The baseline data provided in this project are the initial experiments, and these experiments should be ongoing.
Step 6	Design and Implement an Adaptive Management Plan • Monitoring • Funding • Governance • Adaptability	Partial. A monitoring plan has been designed, but it has yet to be implemented. Funding and governance are to be determined, and adaptability must come once the management plan is in place.

Table 1: Framework for a sustainable water management plan as suggested by Richter et al. (2008)

For any type of management plan, it is important to understand the context of the specific site. The 300-acre research station is located in the tropical Talamancan Mountains of the province Alajuela and is proximal to three important tourist and conservation regions; Monteverde, Arenal Volcano (La Fortuna), and Children's Eternal Rain Forest Reserve (Figure 1). The property is between 2362.2 ft and 2493.4 ft above sea level. Costa Rica's tropical climate is characterized by a November to April dry season and a May to October rainy season (Leemans & Cramer, 1991). The amount of rainfall within these seasons vary geographically (Nadkarni & Wheelwright, 1999), but historical climate data from 1931-1960 (Leemans & Cramer, 1991) for this region is available approximately 18 miles from the research station at a similar altitude (Figure 1). This region averages 97.7 in rain annually and has an average annual temperature of 72° F (Leemans & Cramer, 1991). The average dry season rainfall is 20.4 in, and the average rainy season rainfall is 77.3 in (Leemans & Cramer, 1991). The average temperatures remain relatively constant throughout the year, with an average dry season temperature of 72.1° F and 71.9°F during the rainy season (Leemans & Cramer, 1991).

Figure 1: Map depicting the research station location, three important tourist and conservation areas as spatial references, and the nearest atmospheric gauging station.

The physical setting of the research station itself is also important for a management plan. TCU's tropical research station is situated on approximately 300 acres with one house for the owner, a house for the ranch hand, a barn, two cabins which will house TCU faculty, and the dormitory which has a 20-student capacity (Figure 2). The dormitory is approximately 0.3 miles from the faculty cabins, and these cabins are approximately 0.3 miles from the two houses (Figure 2). There are several streams within the property boundary that all flow in to the San Lorencito River. The San Lorencito River itself is the northwest boundary of the property, while a smaller, unnamed stream borders the west side of the property (Figure 2). These on-site streams serve as the water sources for the property. There are two water sources; one provides water for the dormitory while the other provides water for the houses and faculty cabins.

The research station property was purchased by Gustavo Orozco in 1993 with the intent of leasing it to an American university (Orozco, *personal communication*). Mr. Orozco and a full-time ranch hand (both Costa Rican nationals) reside permanently on the property. Currently, there are no electricity, internet, or phone services on the property. A generator provides electricity for a few hours at night for the dormitory when students and faculty are visiting.

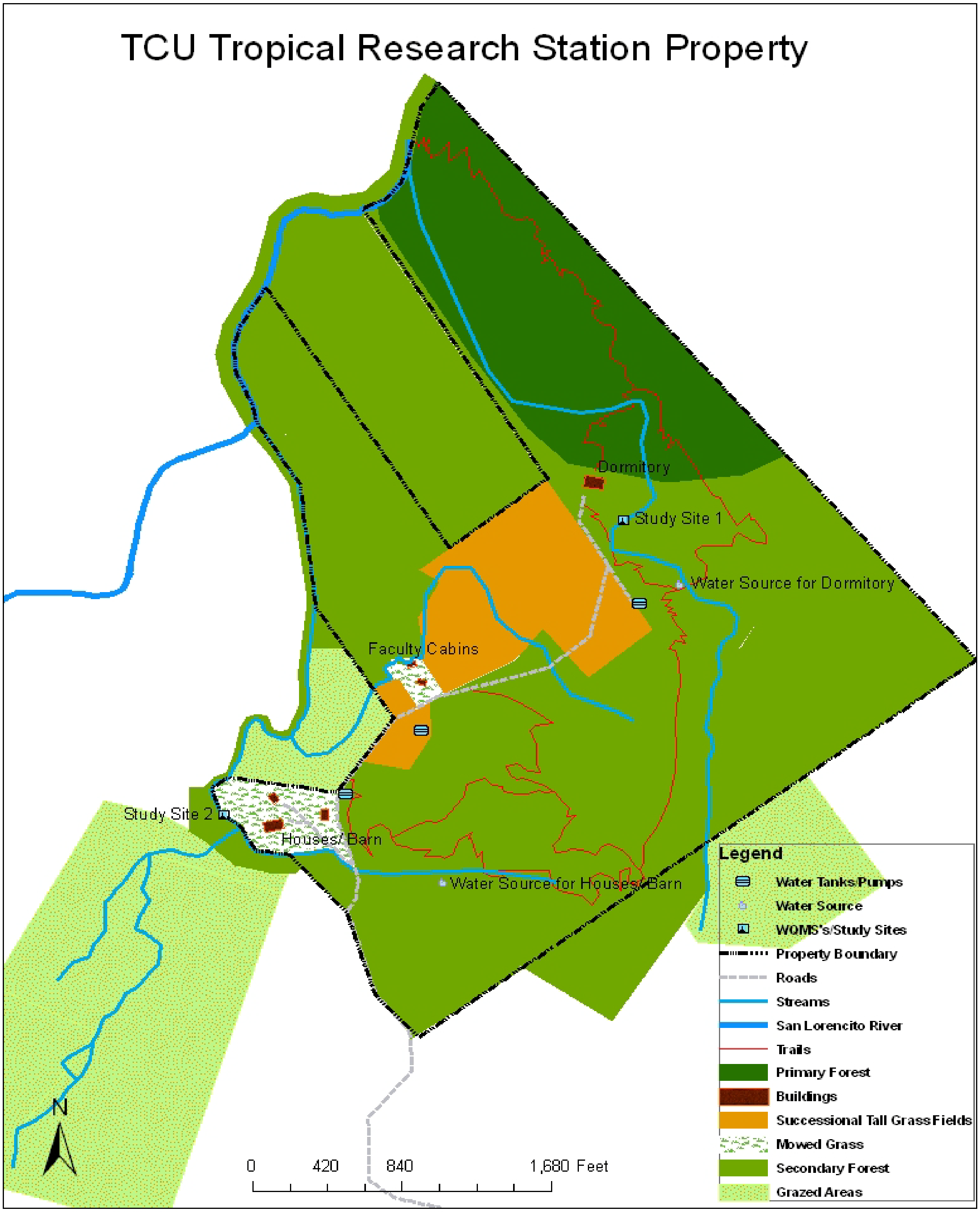


Figure 2: Map of the TCU Tropical Research Station, including some surrounding area land use. (Data and locations collected on-site through extensive field mapping.)

Within a ten-mile radius of the research station there are cultivated pastures used for raising cattle and horses and fields for growing ornamental plants commercially. Land cover on the research station property consists of primary and secondary forest, successional tall-grass fields as a result of deforestation, a small tract of fruit and vegetable production, and mowed grass surrounding housing (Figure 2). The property's riparian zones are forested buffers less than 30 feet wide, with the exception of approximately 328 ft of the south bank of the stream near the permanent resident housing which is maintained lawn (Figure 2).

Land cover and land use are major determinants of water quality, biotic integrity, and stream behavior (Griffith et al., 2002). For example, riparian grazed pasture soil generally has much lower precipitation infiltration rates compared to the soil of a woodland riparian zone (Burt & Slattery, 2005) because livestock remove vegetative cover and compact the soil (Brooks et al., 1997). Consequently, grazed pasture has higher runoff and soil erosion than forested buffer zones which can increase stream sediments/ turbidity, and decrease water quality (Chang, 2006). Water quality is determined by measuring factors such as pH, temperature, dissolved oxygen, oxidation/ reduction potential, turbidity, nutrient levels, among others (Gordon et al., 1992). Also, high levels of bacteria, especially fecal coliform, can pollute streams where livestock is raised (Brooks et al., 1997). Cattle and horses are raised on properties neighboring the research station, which are depicted in Figure 2 as 'Grazed Areas'.

The forested riparian buffer zones provide many benefits for the local watershed. Chang (2006) notes that forested basins have high infiltration and high soil-moisture holding capacities due to influences of organic matter of leaf litter, forest canopy, and root systems. The extensive root systems of the tropical trees stabilize the soils that would otherwise be highly erosive due to the steep topography (Chang, 2006). This anchoring is caused by the trees' transpiration rates, which induces the roots' water uptake, exerting a suction effect on the soil (Dingman, 2002). This matrix suction increases soil cohesion, which increases a soil's shear strength (Chang, 2006). A higher soil shear strength yields lower sediment erosion rates, and suction from tree roots is greater than other plant growth forms, such as grazed grass (Chang, 2006). Thus, forested riparian zones have high soil shear strength and decreased rates of erosion, so turbidity (one measurement of water quality) can be much less than that of water surrounded by grazed pasture (Brooks et al., 1997). Tree roots also open up soil pores' spaces, which increases infiltration and reduces runoff and sedimentation rates (Chang, 2006). The forest canopy also intercepts high-velocity raindrops reducing direct impacts on the soil surface (Chang, 2006). Furthermore, fallen leaves from the canopy accumulate on the forest floor, which shields the soil surface (Dingman, 2002). Thus, the forest canopy and leaf litter reduce soil compaction and erosion. The leaf litter also reduces the speed of overland runoff allowing more time for the soil to absorb water (Chang, 2006). This increased absorption also decreases downslope stream sedimentation, which is yet another reason streams with forested buffers have lower turbidity and suspended sediment than streams with grazed grassland riparian zones (Chang, 2006). During the field work of this project, there was a presence of leaf litter on the forest floor. The distinguishable rainy and dry seasons and the tropical deciduous trees of Costa Rica, like those at the research station, leave a mat of leaf litter on the forest floor at least part of the year (Chang, 2006). The forest floor is also heavily vegetated with ferns and other low-growing plants. It is important to note, however, that steep slopes can have high runoff rates even though they are forested (Brooks et al., 1997). Most riparian zones on the property are steeply sloped and densely forested with the exception of one flat stretch of stream behind the owner's house that is bordered by a maintained lawn (Figure 2). Equally notable is that often there is no detectable evidence of stream degradation on grazed lands for several years (Pereira, 1973). Erosion and runoff rates are variable and episodic. They were not measured as a part of this study but are nonetheless processes that need to be understood as part of a water management plan.

Erosion and runoff are important issues for the property's watershed because the soil, classified as a ferri-humic umbrisol (Figure 3) by the Food and Agriculture Organization, can have high erosion rates on steep slopes during heavy rains (ISRIC, 2009). Umbrisols have an umbric horizon and no other diagnostic horizons besides anthropedogenic, albic, or cambic horizons (ISRIC, 2009). Umbrisols have high organic matter content and very good drainage with a high infiltration rate (ISRIC, 2009). Ferri-humic umbrisols are umbrisols that are strongly weathered clays enriched in iron oxides due to a loss of silica ('ferri') with a high humus content ('humic') (Schaetzl & Anderson, 2005). On flatter topography infiltration could be substantial; however, the research station has steep topography and heavy rains characteristic of mountainous cloud forest. Hence, when riparian forest is replaced with pasture, especially on steep slopes, erosion may carry sediments into the stream at high rates, degrading water quality for its intended uses.

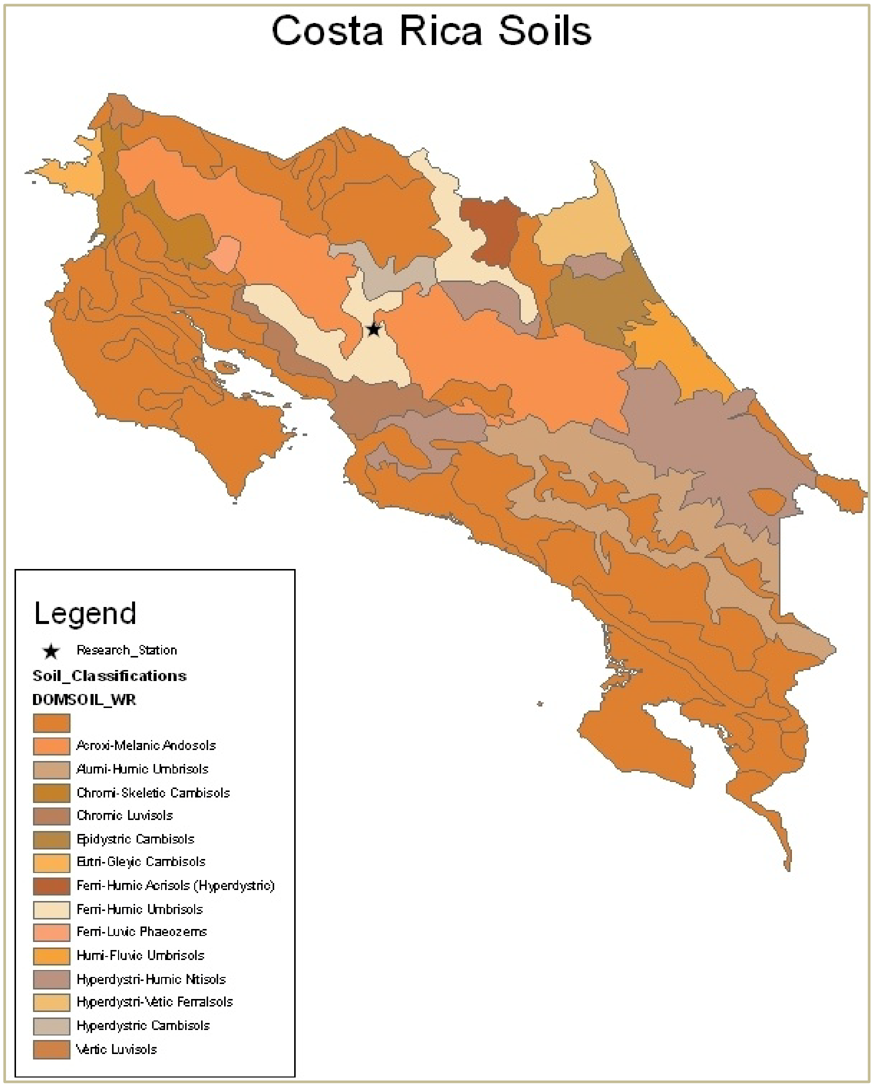


Figure 3: Costa Rica Soils using the Food and Agriculture Organization classification system.

There are three general human uses of water: irrigation, commercial/ industrial, and household/ hygiene (Gleick, 1998). Currently, the intended uses of the research station's streams are for irrigation and household use. A small tract of land is dedicated to growing food sources, but this has reportedly not affected water use because the area is small (about 5' x 20') and the plants were selected because their water, soil, and sunlight requirements are adapted to the conditions of this climate (Orozco, *personal communication*). Most water extracted is used by two adults year-round for household and hygiene. The local stream also supplies TCU visitors for cooking, cleaning, and bathing. So far, TCU researchers have not made a large, continuous impact on water supply. There have never been more than seven researchers at a time staying for longer than a week, and visits total approximately five weeks of the year. Drinking water is currently purchased in large, 10-gallon bottles, and is not presently an intended use of the local stream.

The water supplying the houses comes from a stream impounded by a small dam of rocks (Figure 4), where a 3 ½" diameter pipe draws the water to a circulation tank (Figure 5) that sends water to holding cisterns via a 1½" pipe. When all holding cisterns are full, water from the stream continues to flow into the circulation tank whilst the overflow is discharged just downstream of the dam; so the water constantly circulates when the cisterns are full (Figure 5).

Figure 4: Water source for the houses and cabins. A small dam of rocks was constructed to pool the water, allowing a 3 ½" pipe to capture the water and send it to a holding tank. A similar structure is used at the water source for the research station, as well.

Figure 5: Circulation tank allows constant movement of water when all supply tanks are full. A similar structure exists at the research station water source.

Figure 6: Two holding cisterns send water to the houses by force of gravity. The other cistern sends water to the tank in figure 5.

The water then goes through the 1 ½" pipe to the holding cistern where another 1 ½" pipe sends water to the houses by force of gravity (Figure 6). There is a second cistern next to the houses' supply cistern that moves water to a tank by the road where the water is pumped to a cistern on a hill (Figure 7). The water is then sent to the cabins by force of gravity through a 1 ½" pipe. A similar dam-and-circulation tank system serves as the research station water source, and one tank sends water to the research station by gravity. The entire fresh water supply system is depicted in Figure 8.

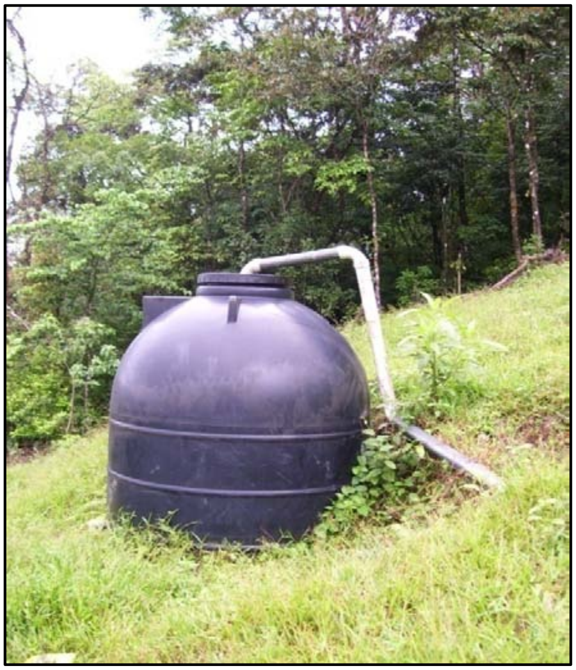


Figure 7: Tank sends water to the cabins by force of gravity.

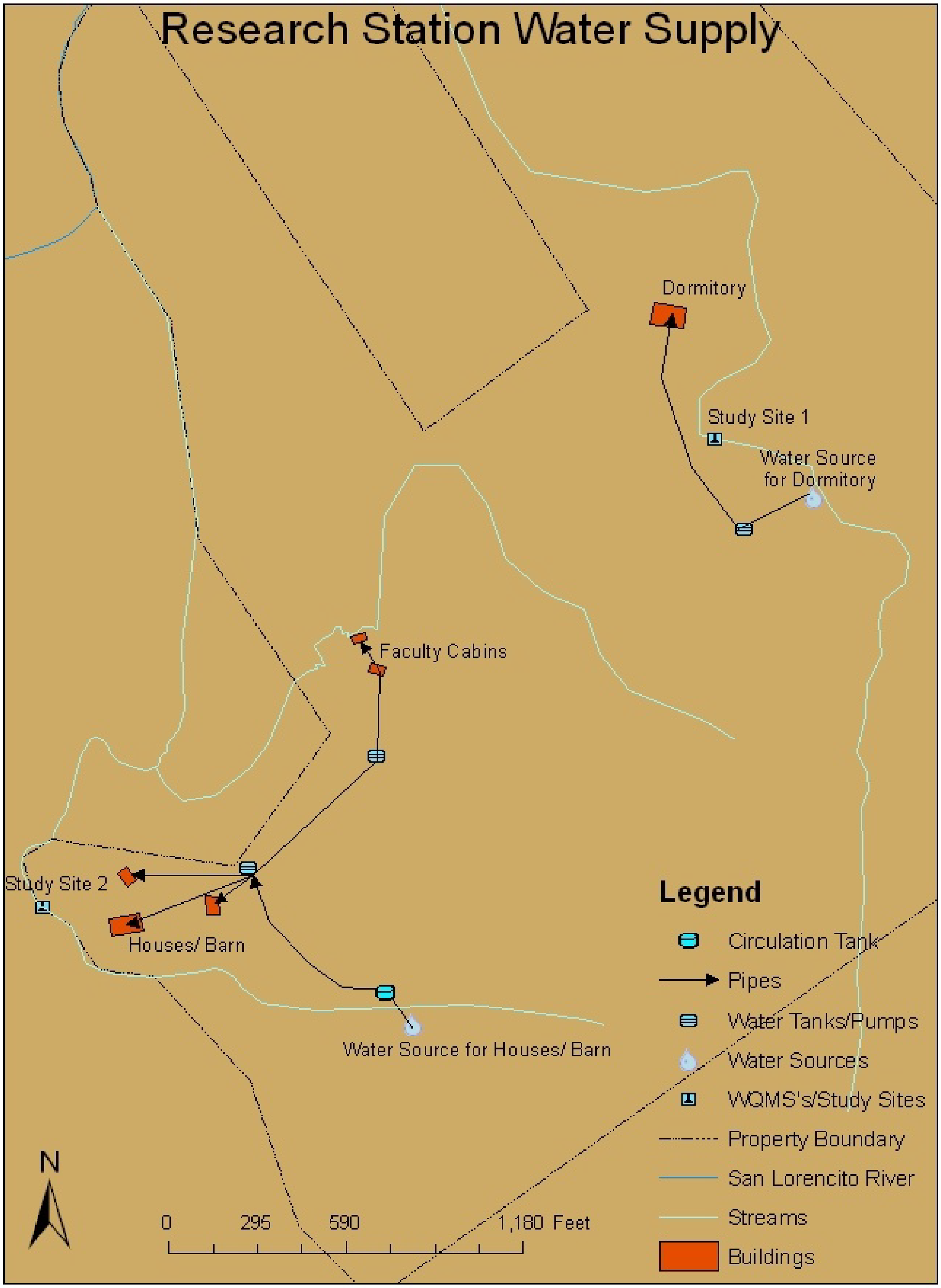


Figure 8: Map of the property's fresh water supply.

Plans are being made for more water extraction. For example, additional plants in the aforementioned vegetable garden will need some irrigation during the dry season. While it is unknown how often the food crops would need irrigation, one ½” hose discharges about 630 gallons of water per hour (Washington Suburban Sanitary Commission, 2009). Three laundry machines will be installed, which on average use 60 gallons of water per load (Washington Suburban Sanitary Commission, 2009). If the research station is at capacity of 20 students and they stay at the station for a week, 10 or more loads of laundry are possible. This would add up to 600 gallons of water used for laundry alone. When TCU students and faculty begin occupying the research station more frequently and for longer visits, there will be a significant increase in water use for cooking and personal hygiene. For example, one toilet flush uses 5 gallons of water (Washington Suburban Sanitary Commission, 2009), and at the 20-student capacity it is likely that 100 gallons of water per day will be used for toilets. Additionally, the average shower uses 5 gallons of water per minute (Washington Suburban Sanitary Commission, 2009). Again using the 20-student capacity, it is possible that the dormitory would use 1,000 gallons of water per day for showering. With this potential water use, the research station owner decided there should be a back-up water source in the case of a severe drought (Orozco, *personal communication*). His plan is to construct a well, which will draw from groundwater that feeds the nearby stream (Brooks et al., 1997). Hydroelectricity generation is also a possible addition to the research station, although as of now, no definite plans have been made. This would reduce flow in a section of the stream between the extraction point and the discharge site much farther downstream (Orozco, *personal communication).* This could have serious impacts on aquatic life (Brooks et al., 1997). Additionally, filters and screens may be installed to make the tap water safe for drinking, which will also increase water extraction as these water sources are currently not used for drinking water.

Although future research station use is uncertain, realistic projections can be made. Assuming that one person uses an average of 50 gallons of water directly from the streams per day (Gleick, 1998), and there are five people staying at the station for a week, then the water extraction rate is approximately 3,500 gallons per week. The implications of this projection will be discussed later in this thesis.

Projected water use conveys the importance of having a stream monitoring program, which can be an invaluable educational tool in many ways. This program could teach students how to manage water responsibly. For example, students may see first-hand how their water extraction affects populations of other organisms. In particular, freshwater organisms such as aquatic insects are sensitive organisms at a high risk of extinction (Revenga et al., 2005). In fact, some studies suggest that aquatic ecosystems can be threatened when stream flow is decreased by just one third (Wallace et al., 2003), especially during droughts. This is just one way to explore the 'life relationships' at the research station, and this issue is applicable to the rest of Costa Rica and the world where deforestation and human impact on land use have affected many species' populations.

This stream monitoring program can also be an educational tool on the ramifications of climate change for water supply. In the summer of 2008, the water levels at the research station were extremely low due to a severe drought (Orozco, *personal communication*). With the impending effects of global warming, students may see even more decreases in water levels and increase in droughts. This issue coupled with the fact that more students will be utilizing the research station over time poses the question: how might the proposed development of the research station be affected by the decreasing water availability? This is a microcosm of these global issues in that the TCU visitors are analogous to a growing population’s increased demand for freshwater that is being reduced by global warming. It is a tough lesson, but it may spur ideas for solutions.

In fact, solutions to other problems may arise from stream monitoring. Most water issues, such as poor water quality and changes of habitat structure, flow regime, food sources and biotic interactions are anthropogenic (Karr & Chu, 1999). As noted earlier, land use can have significant effects on stream health. Transforming a forested riparian zone to a grazed pasture can lower the water quality, destroy forest species' habitat, produce flashier stream flow, and alter the stream's biotic integrity (Pereira, 1973). However, monitoring programs are effective alerting devices for these water issues, and changes observed in streams' qualities and characteristics can inform timely responsible and sustainable water management decisions before the streams have been critically degraded.

This project provides baseline hydrology data during the dry season for the research station, to be used by future researchers to compare water quality and quantity. With this baseline data, the streams' physical, chemical, and biological properties are evaluated at a time when both water extraction and flows are minimal. Physical properties, such as stream characteristics, stream temperature, surrounding land use, topography, and others, are helpful in understanding stream classification and processes (Gordon et al., 1992). Chemical properties, such as dissolved oxygen, salinity, pH, and others can be used to define water quality and encompass many measurement types (Gordon et al., 1992). Both the physical and chemical properties are important to this project because the local water quality should not be degraded to a state that threatens the existing biological stream properties. The biological stream properties are described from collections of aquatic macroinvertebrates, which indicate current stream health conditions (Fenoglio et al., 2002). Due to the significance of geographical information systems (GIS) in freshwater studies and ecological management programs (Heartsill-Scalley & Aide, 2003), maps are integral components to assess the landscape at the research station. Finally, this project recommends an ongoing stream monitoring protocol based on a review of three established programs from developed countries (the U.S. and South Africa) because no monitoring protocol was found for

Costa Rica. For the research station to have a sustainable water supply, a long-term stream monitoring program must be established. The physical stream descriptions, water quality measurements, sediment transport measurements, invertebrate samples, and maps provided in this project may be integrated and used in future research for a more comprehensive understanding of the watershed.

STUDY SITES AND METHODS

Because the outcome of this project is to provide baseline data, two study sites were chosen *a priori* to represent polar ends along a stream health spectrum for this particular location. Study site 1, representing a healthier, more pristine stream, is located at -84°33.305028', 10°15.117873' (see Figure 2), near the dorms at the station. It is approximately 164 ft downstream from the dormitory's water source (see Figure 8). Study site 2 (-84°33.680983', 10°14.862319', see Figure 2) is located just downstream from the water source for the houses and cabins, near the entrance to the research station (see Figure 2). The water source is approximately 656 ft upstream in an undisturbed, densely forested stretch of stream (see Figure 2). As this stream flows past the houses, a tributary enters the stream from offsite. The tributary drains deforested slopes and an area impacted by grazing. Study site 2 was intentionally selected just below the confluence of this offsite tributary and the water source to assess potential grazing impact on this stream.

First, the physical properties for both streams were assessed. Land use within at least 50 ft of both stream banks was noted as either forested, grazed grassland, or maintained grass (see Figure 2). Stream order (based on Strahler, 1952), stream substrate (Gordon et al., 1992), presence of riffles, presence of organic material, and bank slope were recorded. Each basin was assessed by walking all stream lengths noting land use, topography, or any other identifying features, all presented in Figure 2. Two gauging stations were established, one at each study site. Detailed channel cross-sections, also known as the velocity-area method described by Dingman (2002), were made at each site (Figures 9 and 10). Channel depth was measured every 2 in across the stream, and these depths were used to find the average area of every 2 in cross-section to compute accurate discharge.

Figure 9: Taking cross-sectional data at study site 1.

Figure 10: Taking cross-sectional data at study site 2.

A Water Quality Monitoring System (WQMS) (Global Water, Gold River, California, USA) was installed at each gauging station to determine chemical properties, stream temperature, and stage for each station. The WQMS contains sensors that were programmed to log temperature, conductivity (salinity), percent saturation of dissolved oxygen, and water level every three hours. Conductivity level, used to estimate dissolved solids (Environmental Protection Agency, 2006), also yields a potability classification for the streams (Table 2).

Potability Classification	**Range of Conductivity (µS / ft)**	**Beneficial Use(s)**
Fresh	<9906	Potable
Marginal	>9906 but <29,718	At the limit of potability
Brackish	>29,718 but <99,060	Non-potable, usable for irrigation
Saline	>99,060	Non-potable, usable for industry or salt-tolerant livestock

Table 2: Classification of Potability Based on Conductivity (Hart, 2002).

The sensors were installed in a 4-inch diameter pvc pipe that acted as a stilling well along a channel bank. A tipping-bucket rain gauge was installed at each station and programmed to sample cumulative rainfall every 3 hours. The WQMS at study site 1 was installed on 01/16/2009. Due to a battery malfunction, data logging ended on 03/12/2009. The WQMS at study site 2 logged data from 1/16/ 2009 to 05/18/2009. The WQMS logging times along with seasonal climate data are presented in Table 3. Two YSI OMS600 turbidity probes were installed, one at each site, and programmed to record turbidity levels in nephelometric units (NTU's) every 6 hours. A probe malfunction at study site 2 resulted in loss of data, so no turbidity data is reported for that site. This data provides an optical measure of water clarity and will eventually be calibrated against measured suspended sediment so that sediment flux from the two basins can be assessed. pH was recorded one time at each study site on 05/19/2009.

	Data Log Start Date	**Data Log End Date**	**% of November-May Dry Season**	**Average Historical Rainfall (Inches) of Logging Dates**	**Average Historical Temperature (Fahrenheit) of Logging Dates**
Study Site 1	1/16/2009	3/12/2009	50%	5.08	72.14
Study Site 2	1/16/2009	5/18/2009	80%	18.3	72.86

Table 3: Data logging dates and their corresponding historical average climate data.

Ultimately, channel response was assessed by plotting stage against rainfall for both stations. Discharge could not be calculated during this study because flows were generally low and a statistically significant stage-discharge relationship could not be established. Nonetheless, considerable information on channel and basin response and likely runoff mechanisms could be gleaned from the stage-rainfall relationships. The rainfall data from study site 1 was discarded because upon collecting data, the rain bucket was found clogged with debris and water had accumulated within the gauge, so all rainfall data used in this project was taken from study site 2 (and probably did not significantly affect results because the study sites are approximately 1 mile apart). Stream velocity was measured by the station owner using a hand-held flow meter on eight occasions during the study period. It plotted against stage to provide preliminary data for the range of flows during the measurement time frame.

Biological characteristics of the streams were measured by sampling aquatic macroinvertebrates in early January during mid-day using a D-frame kick net with a 500-micron screen (Bioquip, Rancho Dominquez, California). Five samples were taken from each of the two streams. Each sample was taken 16.4 ft downstream from the previous sample, starting at the WQMS's and moving downstream. The substrate was disturbed for 1 minute by kicking or rubbing the downstream side of a boulder just upstream from the net (Merritt et al., 2008). The specimens were placed into alcohol and later identified to family by Dr. Allison Davis-Stamatis based on Merritt et al. (2008). The specimens were used to indicate the health of the benthic habitats by applying two ecological indexes; the Simpson's Index (1/D) (Simpson, 1949) and Biological Monitoring Working Party Index (BMWP) (Armitage et al., 1983). Simpson's Index, ranging from 0-1, measures the diversity of the populations collected, where 0 is very high diversity and 1 is very low diversity (Simpson, 1949). The Simpson's Index was selected because it accounts for relative abundance of species, but it is not used to suggest stream health. The BMWP modified for Costa Rica, which yields a number that suggests level of water quality based on the insects' tolerance to pollution, was determined by assigning each family a pollution-tolerance value ranging from 0-10, 0 being extremely tolerant to pollution and 10 being extremely intolerant to pollution (The President of the Republic Minister of Atmosphere and Energy and the Health Minister, 2007). An average tolerance level was then calculated for each site, known as the Average Score per Taxon (ASPT), and the ASPT ranges from 0-10, where a higher score reflects higher water quality (Rosenberg & Resh, 1993).

Using ArcMap version 9.3 (Environmental Systems Research Institute), several maps displayed throughout this paper were made to assess the current landscape and hydrology at the research station. It should be noted that these digital maps of the area and the work reported here are a first iteration of a broader mapping program planned for the area. GPS readings were taken with a Trimble GeoExplorer 2008 Series in the geographic coordinate system GCS WGS 1984 to mark buildings, roads, trails, streams, water tanks, and other points of interest. This data was digitized in Transverse Mercator projection as polyline, polygon, or point shape files depending on the feature. In some areas of the property, dense forest cover inhibited satellite readings, so the trails were surveyed by reading a compass and counting paces. These bearings were later translated into ArcMap polyline features. Detailed aerial imagery is currently not available, but a 1:50,000 topographic map purchased from Omni Maps (2009) was digitized and converted to a raster file. With this raster file, drainage area was deduced and functions of ArcHydro provided drainage basin area and digital models of the local stream system. This raster file was used to generate a 3-D model of the research station to provide a realistic visual representation of the local topography and hydrology. The U.S. Geological Survey data of Central America (2001) provided some GIS layers, and soil information was obtained from the World Soil Information website (2009). These maps provide a visual simulation of the property and its watershed that this project aims to assess.

Costa Rica passed a water law in 2007 that emphasizes the need to protect water quality and aquatic ecosystems (The President of the Republic Minister of Atmosphere and Energy and the Health Minister, 2007). This law stresses that sustainable development is necessary to maintain a healthy water supply for humans as well as other organisms. The document provides pollution tolerance levels for Costa Rica’s aquatic macroinvertebrates as well as acceptable pollution concentration ranges and parameters of a healthy stream. It does provide a short methodology section, but it is not very detailed, so three other successful monitoring programs were reviewed: a protocol developed for the Kruger National Park in South Africa (Rogers & Bestbier, 1997), a chapter from an environmental monitoring handbook (Hart et al., 2002), and the Environmental Protection Agency's (EPA) manual for volunteer stream programs (Environmental Protection Agency, 2006). The EPA manual is in accordance with this Costa Rica water law and was selected as best-suited for implementation at the research station.

RESULTS & DISCUSSION

Study site 1 was a first order (Strahler, 1952), riffled perennial stream characterized by a boulder substrate on a steep topographic terrain. The water was clear with some leaf litter and algae. The stream at the study site was 9.35 ft wide with an average depth of 0.47 ft when the cross-section was taken; discharge was 0.042 ft^3/s at this water depth (Figure 11). A second cross-section taken on May 19, 2009 resulted in a discharge of 0.027 ft^3/s when the stream was 6.23 ft wide with an average depth of 0.36 ft. The projected water use for the researchers, as mentioned in the introduction, of 50 gallons per day per person is equal to 0.002 ft^3/s/person. At the 20-student capacity, this projection and the extraction rate becomes 0.04 ft^3/s. This is potentially problematic for stream biological conditions because it is known that this stream can have a discharge of 0.03 ft^3/s and less. Also, this stream should be carefully monitored for over-extraction so that it does not dry up as a result of human use.

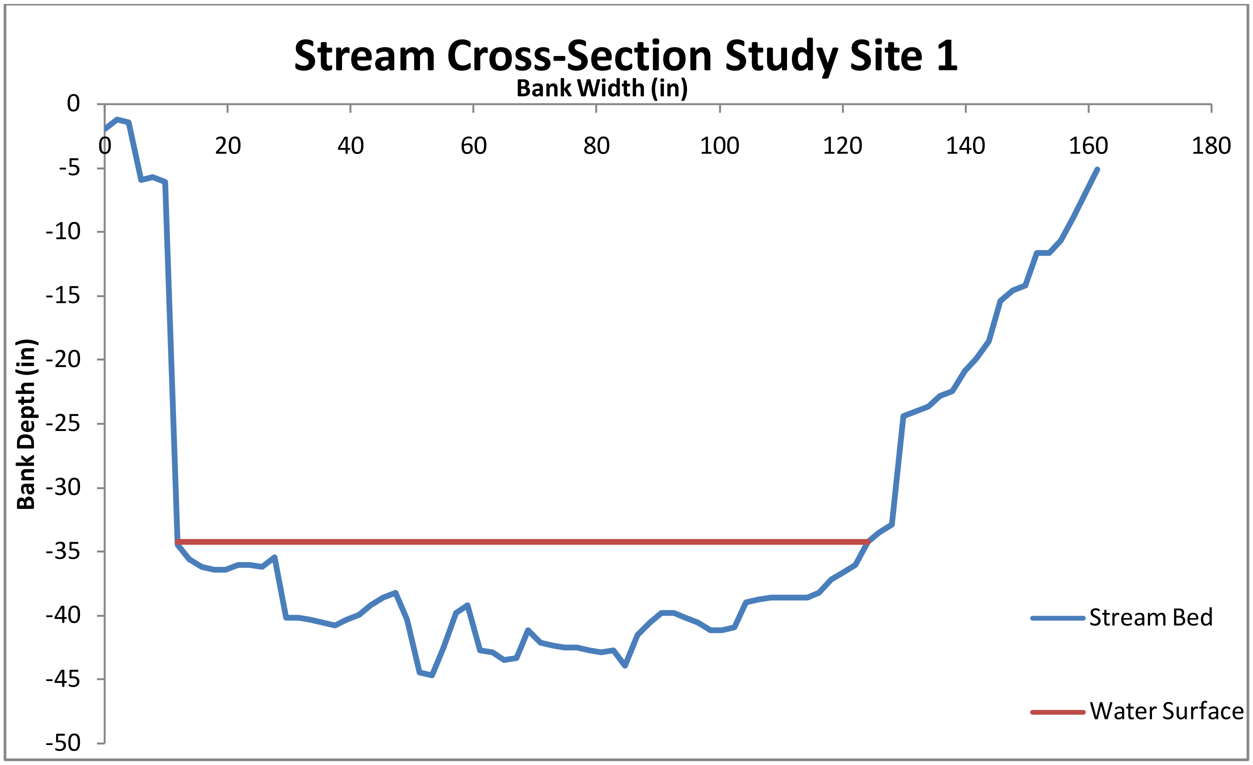


Figure 11: Cross-section of the stream at study site 1 from January 3, 2009.

Looking downstream from study site 1, the left bank was vertical (where the stilling well was installed) and the right bank was steeply sloping (Figure 11). Both banks were heavily vegetated, which provided full shade to the water surface. Near the headwaters of this stream there was a small tract of grazed grassland for cattle. The rest of the stream was densely forested riparian zone to the San Lorencito River (see Figure 2). The average stream temperature at study site 1 was 68.3° F, with a standard deviation of 1.1° F.

Study site 2 was similar to study site 1 in terms of physical characteristics. It was a perennial, highly riffled stream with a boulder substrate, but it differed from study site 1 in that it was a second order stream (Strahler, 1952) on flatter terrain. The water was clear with some leaf litter and algae. The stream was 13.23 ft wide with an average depth of 0.56 ft at the study site when the cross-section was measured. Discharge at study site 2 was 5.31 ft^3/s at this water depth (Figure 12). A cross-section taken on May 19, 2009 revealed an average discharge of 5.41 ft^3/s with a stream width of 13.78 ft and an average water depth of 0.44 ft. Using the same projection of 0.04 $ft^3/s/20$ people, this stream's biological conditions may not be as sensitive to water extraction as study site 1 because it is a larger stream with higher discharge, but that is not to say that this stream should not be monitored.

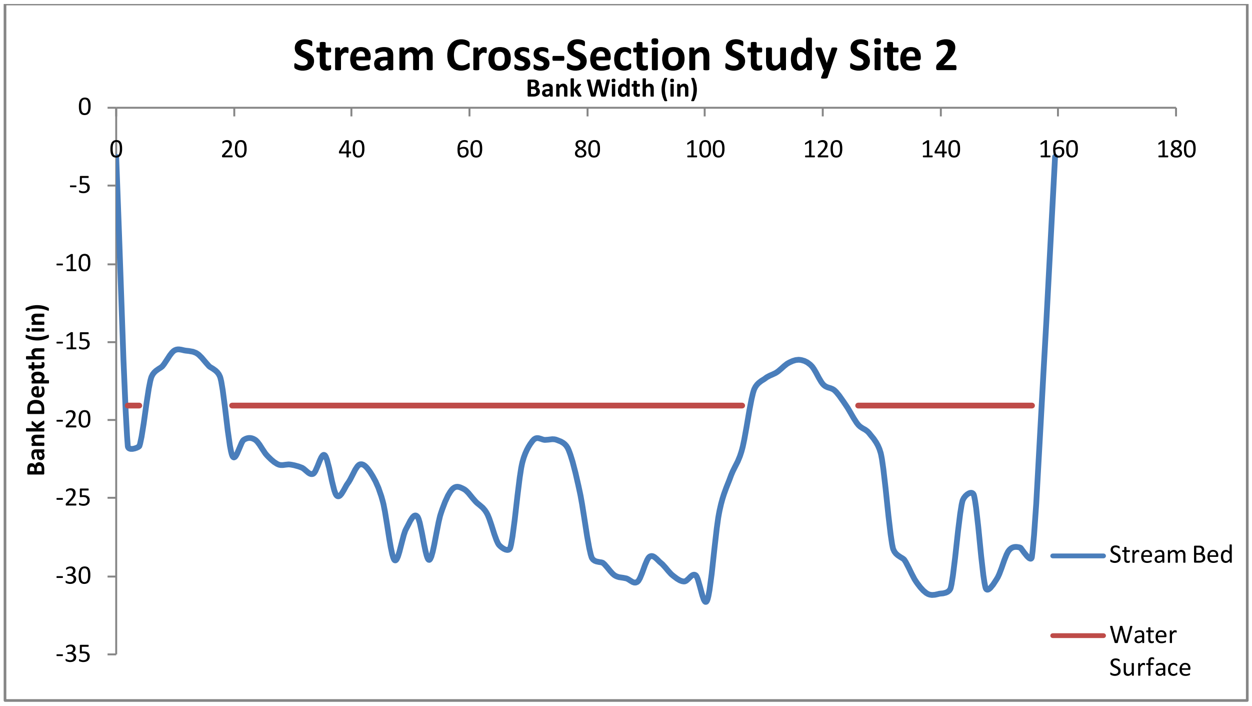


Figure 12: Cross-section of the stream at study site 2 from January 3, 2009.

From the upstream vantage point at study site 2, the left bank was vertical (Figure 12) with a forested buffer zone while the right bank was vertical (Figure 12) and about 25% forest cover, so there was some shade to the water surface. The stilling well was installed on the right bank at study site 2.

Study site 2 was 65.62 ft downstream from where a tributary draining highly disturbed, heavily grazed land empties into the undisturbed stream on the property (which was determined in the field). The grazed area surrounding the tributary has no tree growth and stream-bank erosion is evident due to animals' crossing the stream (Figure 13). Downstream of the WQMS, the stream has forested riparian buffers until the San Lorencito River with the exception of a short stretch of mowed grass behind the owner's house. The average stream temperature at the WQMS was about 3.2° F warmer than study site 1: 71.5° F with a standard deviation of 2.7° F with little seasonal variance. The warmer temperatures were probably partially the result of less dense forest cover and therefore more sunlight on the water surface than study site 1.

Figure 13: Unrestricted access of cattle to the streams causes vegetation removal and erosion into the streams.

Both streams drain into the San Lorencito River, and their drainage basin boundaries are the surrounding high points of elevation. Figure 14 shows the drainage basin area derived from digitizing the topography map. The drainage area surrounding study site 1 is approximately 0.15 mi^2, and the drainage area surrounding study site 2 is approximately 0.75 mi^2. Figure 15 displays the topography that determines these drainage basin areas.

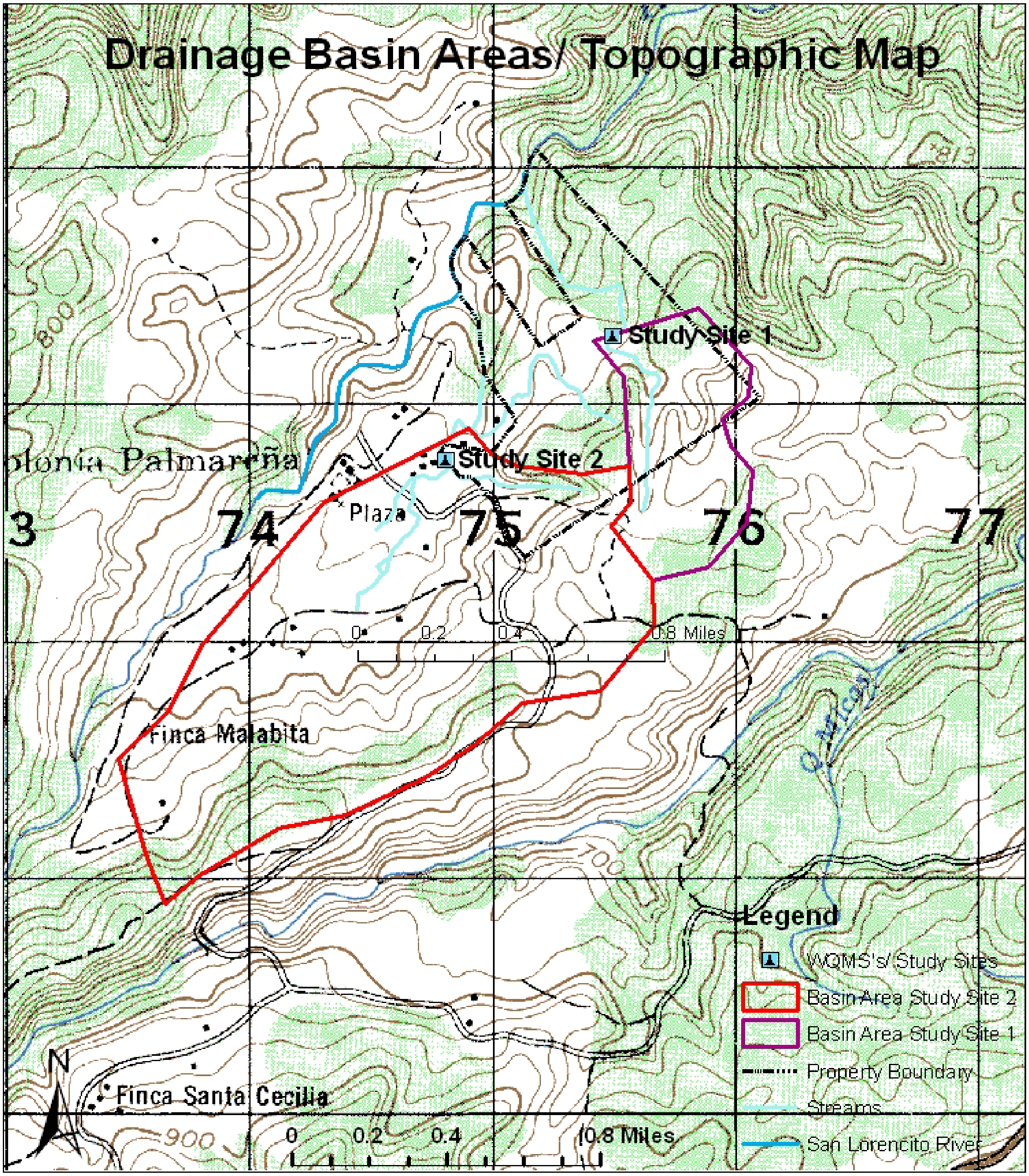


Figure 14: Drainage basin of the research station digitized over the topographic map. Both study sites drain into the San Lorencito River.

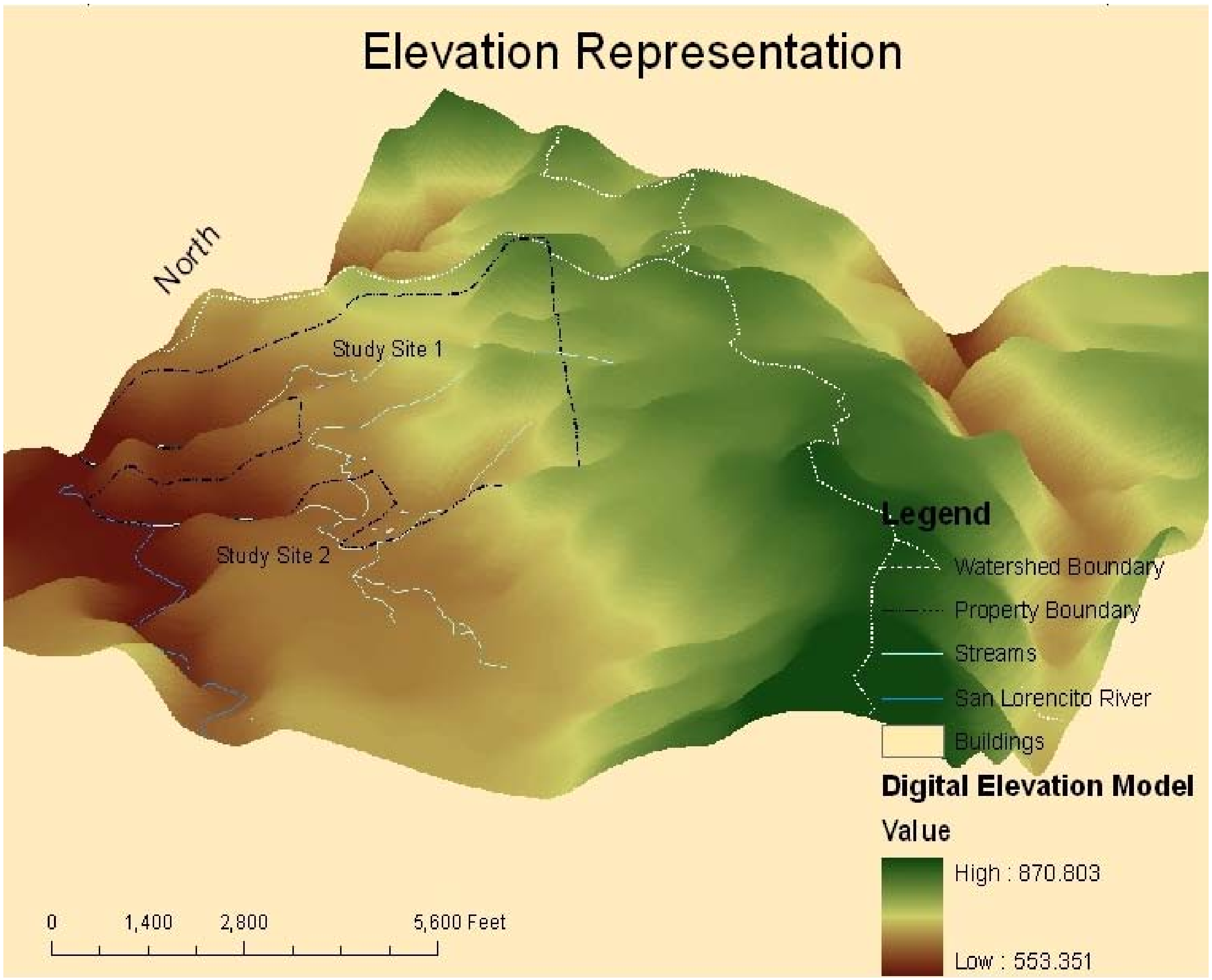


Figure 15: Digital elevation model with a 7X exaggeration displays the local topography along with the stream system. The white dashed line represents the drainage basin boundary. The orientation has been rotated for a better view of the entire property.

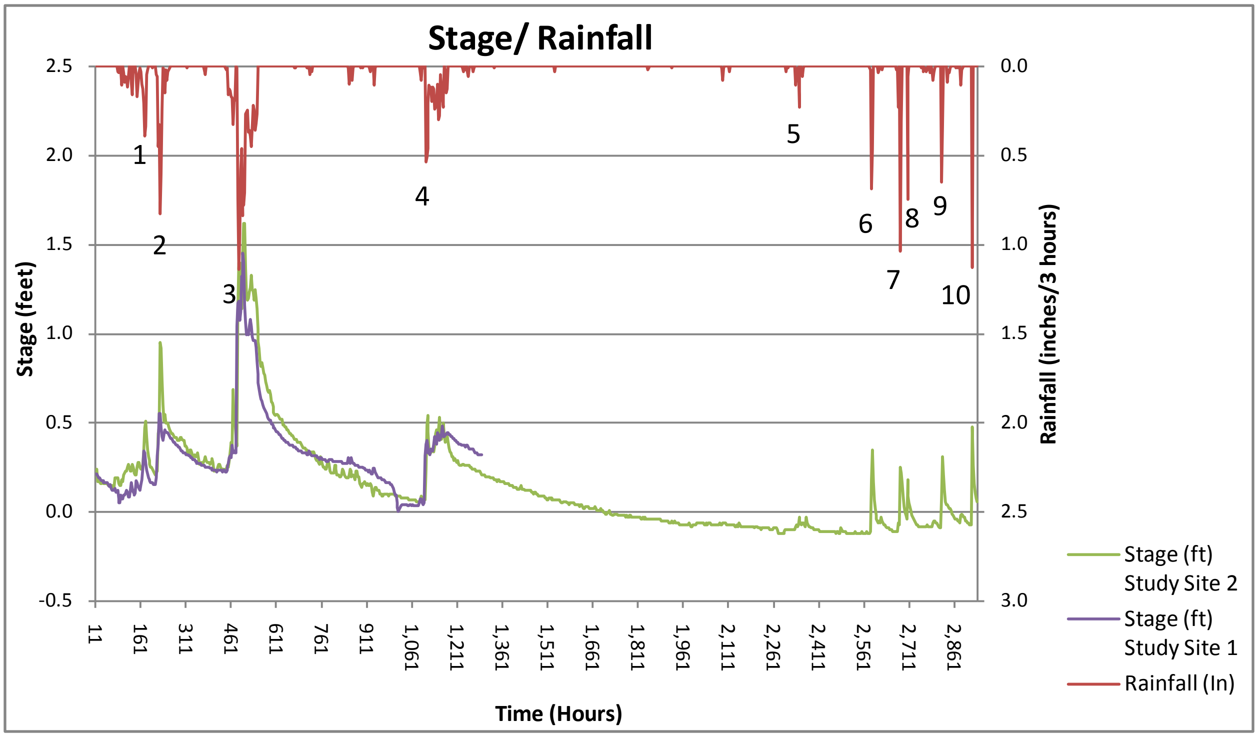


Figure 16: Stage and rainfall plotted over time every three hours. The streams of both study sites are responding very similarly to rainfall events in terms of change in stage. The numbers represent the rainfall events that significantly affected change in water level.

The hyetograph and stage record from both gauging stations are plotted in Figure 16. As noted earlier, discharge could not be computed because no stage-discharge curve could be established from the flow record. Although the two stage curves shown in Figure 16 suggest similar flow rates, these readings are relative, in the sense that at study site 1, the pressure sensor was situated in a deeper pool of water in the stilling well, even though velocity and hence discharge at study site 2 was significantly higher.

Rainfall Event	Time to Peak Study Site 1 (hrs)	Peak Lag Time Study Site 1 (hrs)	Rainfall Event Duration (hrs)	Total Event Rainfall (in)
1	12	9	33	1.57
2	9	6	39	1.64
3	6	3	48	3.01
4	6	6	111	12.52

Table 4: During time of study, there were 4 rainfall events that significantly raised stream stage at study site 1 (see Figure 16). The time to peak is the time in hours for the stream stage to reach its peak. Peak lag time is the time in hours it takes for the stream to reach its peak stage following the peak rainfall rate. Average peak lag time was 6 hours.

Rainfall Event	Time to Peak Study Site 2 (hrs)	Peak Lag Time Study Site 2 (hrs)	Rainfall Event Duration (hrs)	Total Event Rainfall (in)
1	9	<3	33	1.57
2	6	<3	39	1.64
3	3	3	48	3.01
4	6	6	111	12.52
5	3	<3	75	4.95
6	3	3	15	0.42
7	<3	<3	12	1.19
8	<3	<3	18	1.61
9	3	3	6	0.81
10	<3	<3	6	0.99

Table 5: During time of study, there were 10 rainfall events that significantly raised stream stage at study site 2 (see Figure 16). The time to peak is the time in hours for the stream stage to reach its peak. Peak lag time is the time in hours it takes for the stream to reach its peak stage following the peak rainfall rate. Average peak lag time was <3 hours, which means that stage and rainfall peaked within the same 3-hour gauging period. Because lag times were predominately 3-6 hours, average peak lag time was assumed to be only slightly less than 3 hours.

During the time frame of this project, 10 rainfall events at study site 2 and 4 rainfall events at study site 1 resulted in discernible peaks in the stage record. It was found that there were relatively short lag times between rainfall input and stream stage response (Tables 4 and 5). The maximum 3-hour storm event occurred 02/05/2009 between 02:13 and 05:13 with a total of 1.14 in/3 hrs of rain, which was a rate of 0.38 in/hr. The maximum 24-hour storm event started 02/05/2009 at 02:13 and ended 02/06/2009 at 02:13 with a total of 6.82 in/24 hrs of rain, a rate of 0.28 in/hr. Study site 1 responded to rainfall events within 6 hours, while study site 2 responded to rainfall events within the 3-hour logging period of the WQMS's. In other words, water surface elevation increased almost immediately during a rain event and quickly decreased as rate of rainfall decreased. In general, there was no change in stage when the rainfall rate changed by less than 0.01 in/3 hrs. However, this can only be inferred per 3 hours, not every hour. For future data logging, it is recommended that the WQMS's be re-programmed to log every hour to obtain more precise stage and discharge data. The streams of the study sites appeared to behave almost identically even though they were anticipated to respond very differently based on basin land use. While less data is available for study site 1, it may be speculated that this study site would continue to parallel study site 2 in stream response.

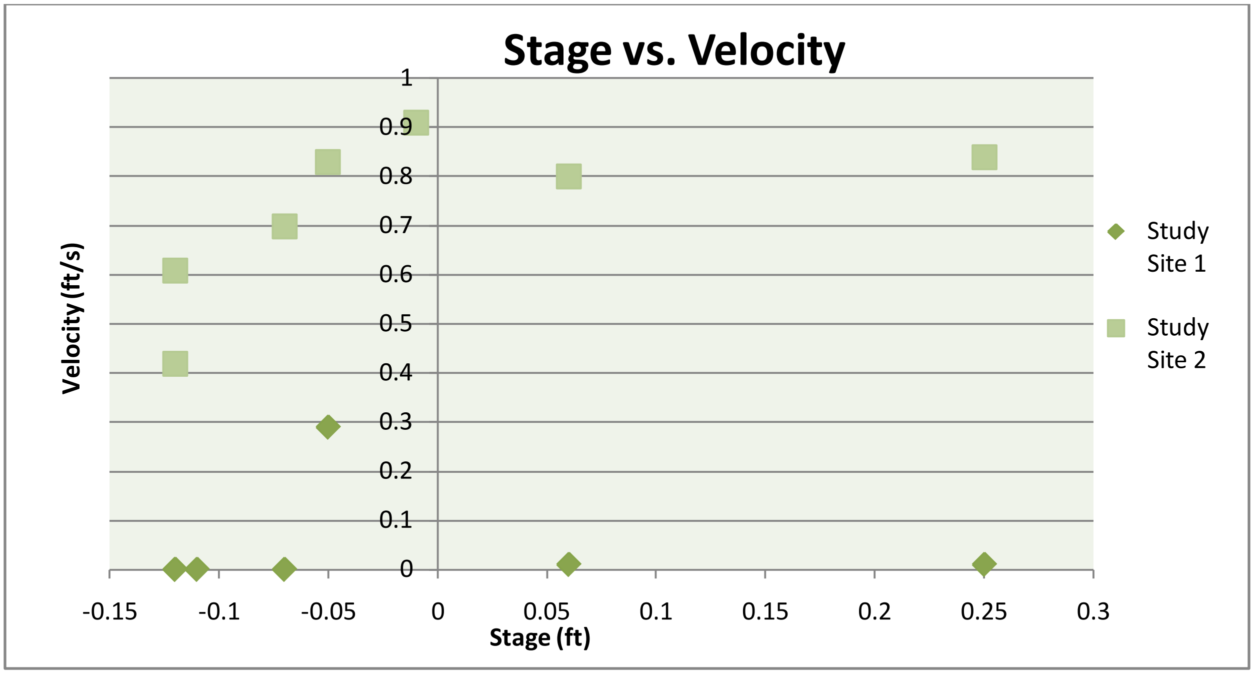


Figure 17: Velocity recorded at each study site plotted against stage data from study site 2.

The stage/ discharge relationship should be considered preliminary for the range of flows reported in this thesis (Figure 17). Stage data was not available for study site 1 for the dates that velocity readings were taken due to the battery malfunction. For the sake of this report, study site 1 velocity was plotted against study site 2 stage readings because the stage trends were very similar for the dates that stage was recorded for study site 1. Therefore, note that the velocity readings at study site 1 are only speculated to be at the same stage as study site 2.

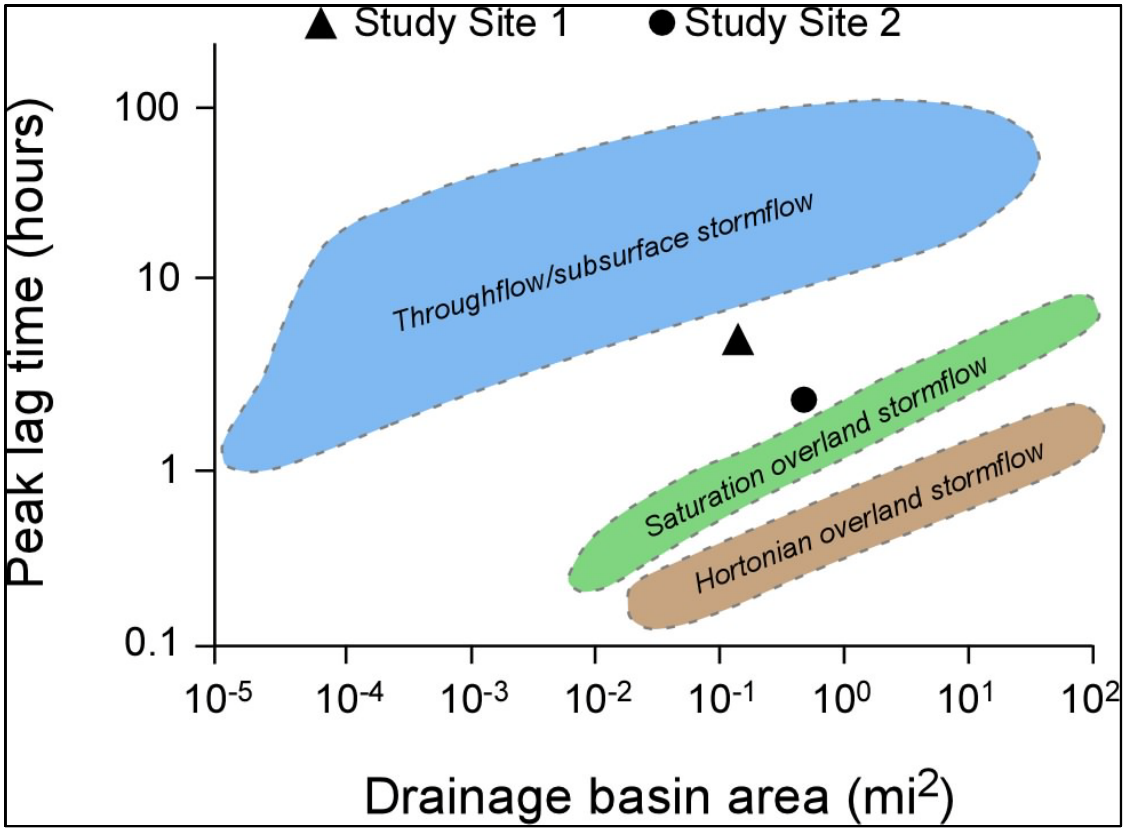


Figure 18: Empirical evidence shows that drainage basin area and peak lag time of change in stage after a rainfall event can determine the predominant runoff processes of the streams (mechanism zones after Slattery et al., 2006). This data provides an average derived from the four and ten rainfall events.

Although runoff generation was not the focus of this study, the mechanisms routing rainfall from the basin slopes to the gauging stations can be inferred, given the peak lag times (see Tables 4 and 5) and drainage areas of both study sites (Figure 18). At study site 1, runoff generation appeared to be a combination of saturation overland flow and subsurface storm flow of the 6-hour average lag time in the 0.15 mi^2 drainage basin area (Figure 18). The processes at study site 2 were predominantly saturation overland flow of the <3-hour average lag time in the 0.75 mi^2 (Figure 18). (Even though average peak lag time for study site 2 was <3 hours, Hortonian overland flow was not a possibility because this process occurs in arid regions or in areas with hard surfaces such as frozen soil or concrete surfaces (Dingman, 2002). None of these conditions existed at the research station.) Saturation overland flow occurs on hillslopes that are saturated from below and a water input (rain) runs off either as a result of the breakout of subsurface water and/ or direct precipitation onto saturated areas (Dingman, 2002). Saturation overland flow is generally most widespread in basins with low, wide valley floors, where a rise in water table during a storm event more easily intersects the surface causing the growth of saturated areas and on slopes with soils of lowered hydraulic conductivity (Dingman, 2002). The results from this study were therefore consistent, given the wider valley in the basin draining study site 2 and the more compacted soils inferred from livestock grazing. Subsurface stormflow occurs on an upslope that is not completely saturated, with steeper valleys and deeper soils, where rain infiltrates and moves laterally through the soil until it is discharged into the stream (Dingman, 2002). Although lag times with subsurface storm flow are generally much longer than the three to- six hour times (as are reported here), much of the water discharged into the channels in this basin was most likely the result of rapid groundwater mounding and the flushing of pre-storm (or “old”) water into the channel (Dingman, 2002).

It does seem counterintuitive, however, that these study sites are responding almost identically after a rainfall event. *A priori* reasoning would suggest much shorter lag times at study site 2 given the deforested tributary and more obvious human impacts, but lag times of study site 2 are within 3 hours of study site 1 based on the available data. More frequent logging would identify more precise lag time differences. Runoff generation, even in forested basins, is a complex phenomenon with several factors contributing to a particular stream’s response to rainfall. For one, study site 1 was on steeper topography than study site 2, potentially allowing more overland flow causing this stream to respond rapidly to a rainfall event, even though it is densely forested. However, there was no evidence of surface runoff in terms of rills or other obvious connected hydrological pathways. The flatter topography of study site 2 may have allowed higher infiltration rates than was expected. Also, livestock use upstream of study site 2 may have actually decreased overland runoff and increased infiltration, which again seems counterintuitive. Observations in the field, however, revealed that the cattle compact the surface thereby creating depressions across the landscape in the very well-drained, high humus soils. These depressions capture significant volumes of rainfall that would have otherwise runoff as overland flow directly into the streams. Thus, it seemed that the basin at study site 1 was not generating runoff more quickly than expected; rather, runoff at study site 2 was being delayed through large depression storage created by the cattle (Figure 19).

Figure 19: The livestock are creating depressions throughout the landscape in the very porous soil. This cow has made four depressions, and he did eventually make it out.

A final hydrologic observation was the impact of antecedent wetness within the basin. While soil moisture was not measured directly in this study, the muted stage response at study site 2 during the last four storm events of the field season suggested considerable soil water recharge following the almost two-month dry period from 03/06/2009 to 05/03/2009. This observation could be applicable to study site 1 as well (assuming that the stage response would continue to follow that of study site 2 had the WQMS battery not malfunctioned). However, this is speculative.

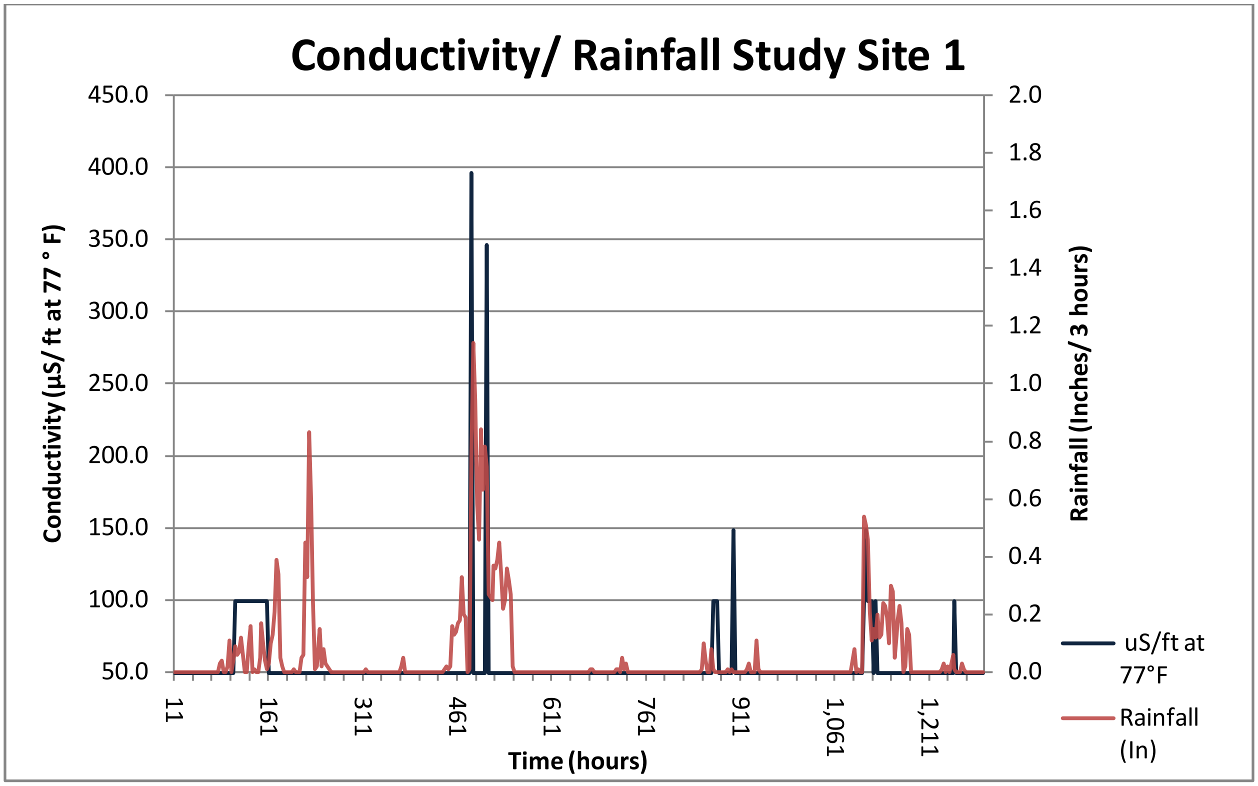


Figure 20: Conductivity plotted with rainfall at study site 1.

Average conductivity for study site 1 was 54.56 µS/ft at 77° F with a standard deviation of 25.60. Conductivity levels increased only during rainfall events (Figure 20). During storm events, conductivity levels ranged between 99.06 µS/ft and 396.24 µS/ft with peak levels reaching 396.24 µS/ft during the third storm event when 1.14 in of rain fell in 3 hours. These levels of conductivity indicated fresh, potable water (see Table 2 (Hart et al., 2002)).

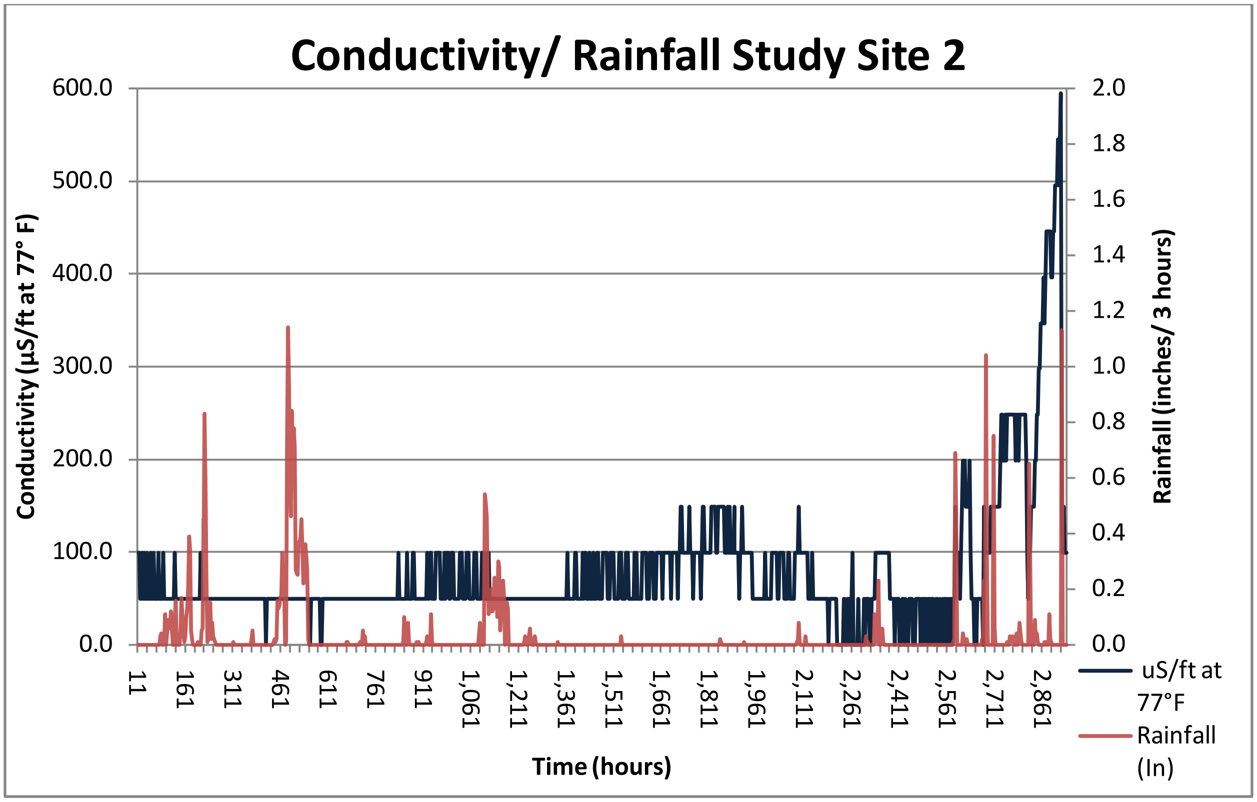


Figure 21: Conductivity plotted with rainfall at study site 2.

Average conductivity for study site 2 was 78.64 µS/ft at 77° F, with one large peak of 594.7 µS/ft at 77° F. Conductivity was much higher and more variable than study site 1 with a standard deviation of 72.85. There appeared to be no relationship between rainfall and conductivity which indicated that some other factor was making the stream at study site 2 more sensitive to changes in solute concentration than study site 1 (Figure 21). One hypothesis could be that there were more solids running off into the study site 2 stream from the grazed areas. Nevertheless, the conductivity levels at study site 2 also classified the water as fresh, potable water (Hart et al., 2002).

The average dissolved oxygen in percent saturation at study site 1 during the course of this project was 62.3% with a standard deviation of 11.2. Percent saturation seemed to increase greatly when stream stage increased (Figure 22). This was most likely attributable to stronger physical mixing of the water when water levels were higher. This average level of percent saturation of dissolved oxygen is considered to be acceptable for most stream organisms (Cary Institute of Ecosystem Studies, 2008).

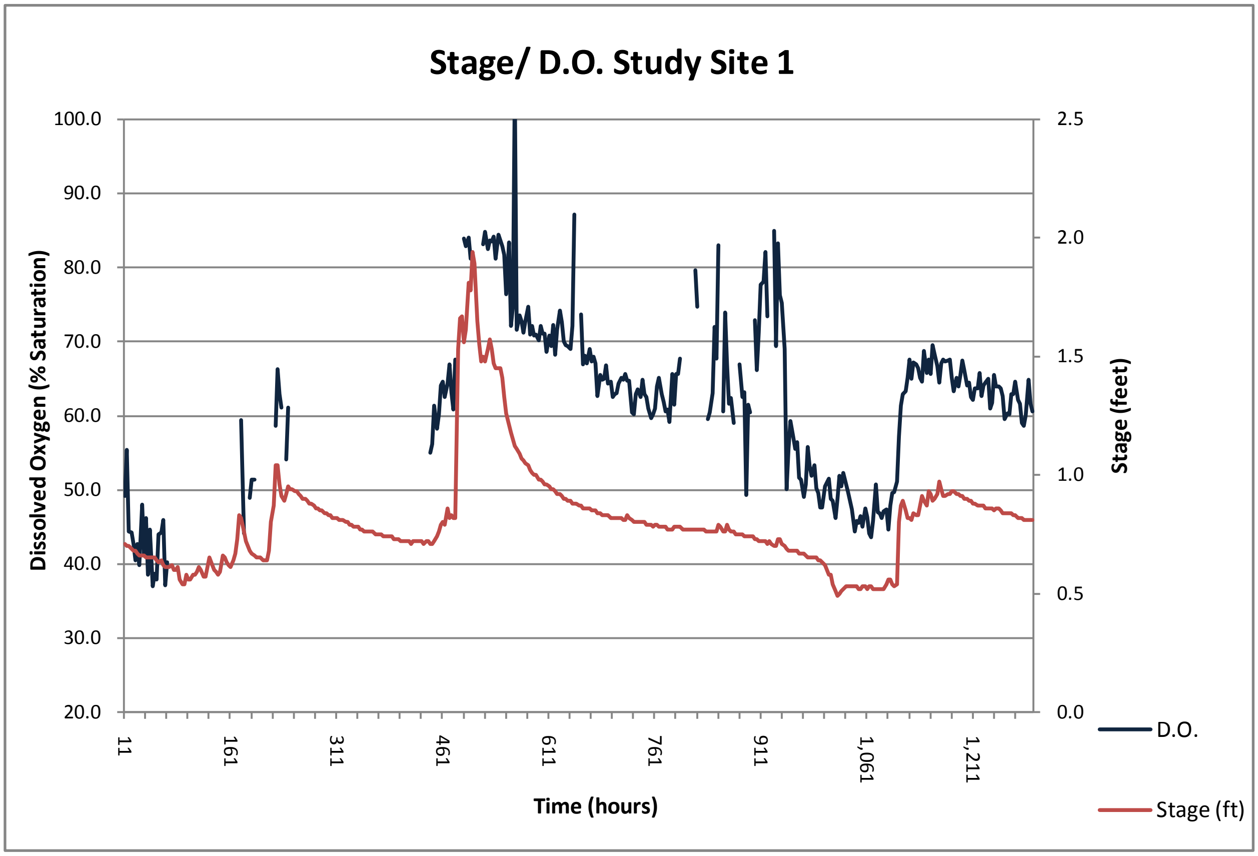


Figure 22: Dissolved oxygen and stage plotted over time at study site 1.

Study site 2 had a significantly lower average percent saturation than study site 1. Average percent saturation was 54.35% with a standard deviation of 6.97. While study site 2 had a lower average percent saturation, it seemed to be less variable at study site 2 (Figure 23). Percent oxygen did not respond with stream stage as quickly as study site 1. Percent oxygen levels did decrease over time as stage decreased, but it was a much slower reaction. This could be attributed to more water flowing through the stream at study site 2 at any given time than study site 1, resulting in more physical mixing which increases DO (Hart et al., 2002). However, this lower percent saturation of dissolved oxygen at study site 2 may indicate that bacteria were using available dissolved oxygen, or the lesser shade cover hence higher water temperature decreased dissolved oxygen. Both of these factors could decrease stream quality because they result in reduced dissolved oxygen (Cary Institute of Ecosystem Studies, 2008). This average level of percent saturation of dissolved oxygen is considered poor quality for stream organisms (Cary Institute of Ecosystem Studies, 2008).

For both study sites, there was not a high correlation between dissolved oxygen and stream temperature even though temperature is a determinant of dissolved oxygen (Environmental Protection Agency, 2006). This may be because stream temperature for the project duration remained relatively constant, so only other factors which affect dissolved oxygen, such as turbidity or biological oxygen demand, would have caused the fluctuations.

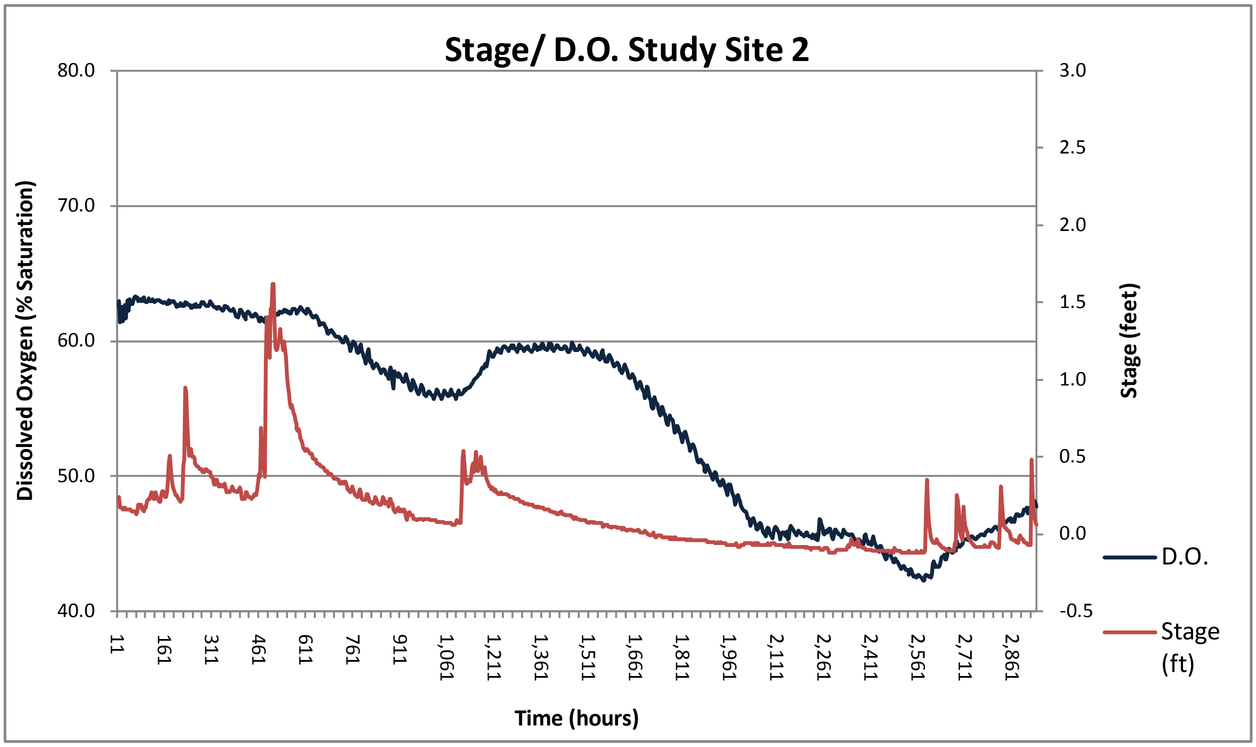


Figure 23: Dissolved oxygen and stage plotted over time at study site 2.

Average turbidity at study site 1 over the course of this project was 69.9 NTU's with a standard deviation of 129.3. Turbidity levels were generally very low indicating optical clarity in the stream. However, there were three distinct turbidity responses: the first started 12:00 on 01/19/2009 when stage increased from 0.6 to 0.83 feet over a period of 84 hours; the second started at 18:00 on 02/03/2009 when stage increased from 0.72 to 1.94 feet over 54 hours; and the third started at 06:00 on 02/27/2009 when stage rose from 0.54 to 0.97 feet over 150 hours. All three events showed clockwise or positive hysteresis (Figure 24) where turbidity (and hence suspended sediment) led the channel response. There was also evidence of sediment exhaustion between events, as shown by the collapse of the hysteresis loops between the first and second hydrologic event. Overall turbidity levels were low and further data over a range of flow conditions would be needed to confirm the significance of the exhaustion noted here. Nevertheless, the second event showed a clear and strong clockwise loop, indicating elevated turbidity (and hence sediment) on the rising limb and flushing during the event.

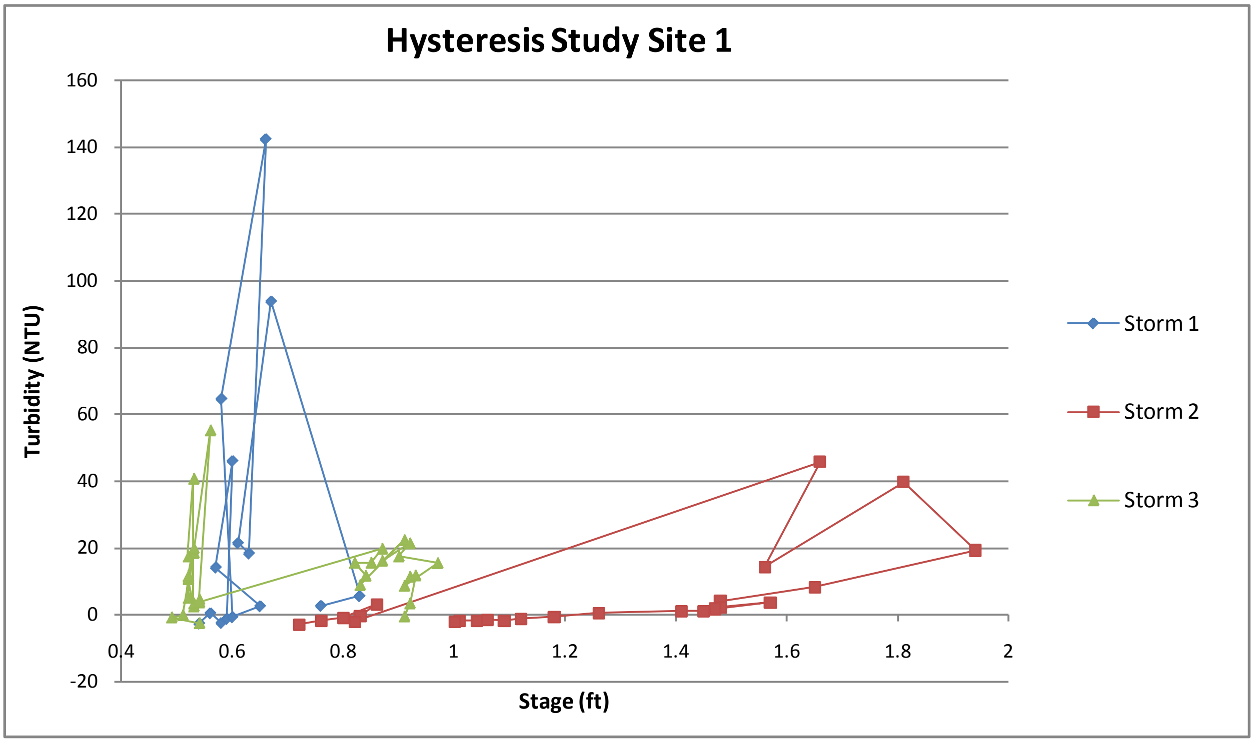


Figure 24: Hysteresis: study site 1.

Overall, the findings from conductivity level readings supported the hypothesis that water quality at study site 2 is impacted more by grazed land than study site 1 because there would be more dissolved solids from livestock. These findings could partially explain the lower dissolved oxygen levels in study site 2 because the suspended solids would absorb more heat and decrease the available dissolved oxygen (Environmental Protection Agency, 2006). Also, it was expected that pH would be lower at study site 2 because the overgrazed basin draining the tributary would have higher levels of nitrification from the livestock, and higher nitrification levels decrease pH (Hart et al., 2002). On 05/18/2009 pH levels for study site 2 were 5.37 as compared to 5.52 at study site 1. However, one reading is insufficient data to make an assertion about the pH of the study sites, so pH should be measured frequently because other factors can decrease pH, such as algal protoplasm (Hart et al., 2002).

Five samples at each study site yielded a total of 43 specimens collected; 23 from study site 1 and 20 from study site 2. Their orders, their families, the numbers of individuals, and their pollution tolerance rankings are depicted in Table 6. Not all of the collected specimens are true aquatic insects, specifically the Pseudoscorpiones (Merritt et al., 2008, Stamatis, *personal communication*), so they are not assigned a pollution tolerance ranking. Some pollution tolerance rankings have not been determined for certain families which are not included in the BMWP Index calculations.

Order	**Family**	**Study Site 1**	**Study Site 2**	**Tolerance Rank**
Ephemeroptera	Baetidae	3		5
	Leptohyphidae	3		5
Plecoptera	Perlidae		1	9
Trichoptera	Hydropsychidae		6	5
Diptera	Simuliidae	5		4
	Unknown		2	N/A
Coleoptera	Carabidae		1	N/A
	Dytiscidae		2	5
	Elmidae	11		5
	Hydrophilidae		1	3
Hemiptera	Veliidae	1		N/A
Blattodea	Blaberidae		5	9
Pseudoscorpiones	Unknown		1	N/A
Annelid	Unknown		1	N/A

Table 6: Results from aquatic macroinvertebrates sampling show the order, family, number of individuals, and tolerance of specimens at each study site.

	Simpson's Index (D)	BMWP
Study Site 1	0.32	4.75
Study Site 2	0.33	6.06

Table 7: Results of the Simpson's Index Equation (1949) and Average Score Per Taxon (ASPT) (Rosenberg & Resh, 1993) based on the BMWP-CR Index as reported from The President of the Republic Minister of Atmosphere and Energy and the Health Minister, 2007

The results from Table 7 suggest that the benthic communities were very similar in diversity (relatively high) and represented similar (average) water quality between the two sites. The insects at study site 1 suggested a slightly lower water quality than study site 2, which is inconsistent with the hypothesis that study site 2 is a more human-impacted basin. These results may be affected by sample size, as relatively few specimens were collected. While the relative abundance of species was similar at both sites, the composition of species was very different as shown in Table 6.

Any recommended stream monitoring program should above all be adaptive (Richter et al., 2003). The results reported here communicate our current understanding of the freshwater ecosystem of the property, but as mentioned earlier, changes in land use on or around the property could mean changes of stream properties and hence a change to the monitoring system. It is also noted that this monitoring program may only apply to those segments or study sites that are being tested. It would be unwise to simply extrapolate this data to other areas of the watershed, i.e. a mile downstream. Keeping this in mind, three successful monitoring programs have been reviewed for the study sites, and one was selected as a best option for the research station.

"Development of a Protocol for the definition of the desired state of riverine systems in South Africa" (Rogers & Bestbier, 1997) discusses the need for a healthy watershed in Kruger National Park and how to attain and maintain the integrity for the watershed's uses. A large portion of the document describes considerations for developing a watershed monitoring protocol and successful outcomes. This protocol is very intensive and requires monitoring of fish and birds as well as other biological, chemical, and physical properties such as a very detailed flow regime monitoring component. The schedule provided for this monitoring is very detailed, and given ample time and resources would be extremely thorough. The intent of this program is to set a "threshold of potential concern," which establishes indicators of watershed degradation. The focus is maintaining the viability of the watershed for current uses, such as swimming, fishing, and other recreation. At the research station, the water uses are very different. While this protocol would be acceptable for this situation, it may be difficult to understand by someone with little scientific background. As mentioned, researchers from diverse educational backgrounds will be visiting the research station, and if they choose to participate in the stream monitoring program, then they may find difficulty in following the Kruger National Park monitoring system.

The chapter entitled *Water* in Environmental Monitoring Handbook (Hart et al., 2002) is a guide explaining the monitoring process and data analysis. It contains descriptions of factors that compromise stream health, especially how water quality can physiologically affect fish. There is also a detailed section on sampling algae, which is a possible project at the research station. This guide ensures minimal errors during data acquisition and it demonstrates data reporting. This handbook also explains the science behind the data collections. This is a guide for toxicology and may be useful should there be evidence of toxins entering the watershed. Because the research station is near headwaters in a remote area with no large developments, toxicology procedures are not yet needed.

The EPA's "Volunteer Stream Monitoring: A Methods Manual" (2006) is the most appropriate monitoring system for the research station given the limited amount of time for monitoring streams. This program complies with the aforementioned Costa Rica water law (The President of the Republic Minister of Atmosphere and Energy and the Health Minister, 2007), and the document is very informative with illustrations and definitions. It is easy to read and understand, so inexperienced students may easily carry out monitoring tasks. It also provides thorough instructions and descriptions for the novice researcher. The monitoring program described in the manual is very similar to the methods of this project, so long-term data may be consistent. Also, this manual provides forms that ensure thorough documentation of data. Due to time, money, or other constraints, not all aspects of the EPA monitoring program may be feasibly adapted. However, it is important to cover as many aspects as possible. Also, other data besides what is required by the protocol should be included. If a student studies something not included in the manual, for example fish populations, this research should be added to the ongoing stream monitoring program and ultimately the sustainable water management plan.

This project is by no means the end of the 'acquisition of learning' for the station's watershed. Others could expand this baseline study into a comprehensive assessment of the local watershed. Table 8 provides some examples of possible research projects that could provide a better understanding of the local watershed.

Area of Study	Project Overview	Project Description
Sociology	Stream Use and Perception	Determine who uses the streams and their perceptions of the streams' health.
Geography	Mapping and Remote Sensing	Obtain detailed imagery of the property. Use remote sensing to map the land use of the regional watershed.
Biology	Species Inventory	List species dependent upon the property's streams. Determine if any resident species are endangered or threatened.
	Stream Biota Resilience	Select or create a disturbed stream segment and monitor its progression/ succession.
Hydrology	Predictive Models	Generate model that predicts the streams' response in flow rates to potential water extraction, drought, and flood conditions.
	Withdrawal Measurements	Determine water stress based on water withdrawal to water availability ratio.
	Runoff Measurements	Determine magnitude of water holding capacity of depressions made by cows because these depressions are delaying runoff as a forest canopy would.
	Hydrograph Generation	Continue to take cross-sections to determine discharge rates. Generate a hydrograph based on long-term (a year plus) data.
	Sediment Flux/ Turbidity Sampling	Intensive examination of basin's differences in terms of runoff, erosion, and sediment flux.

Table 8: Possible research projects to be used in conjunction with the monitoring program to create an extensive sustainable water management plan.

CONCLUSION

This paper is a stepping stone toward sustainable water management at the TCU Tropical Research Station in Costa Rica. Water extraction for human use does not have to compromise stream integrity, and by following the guidelines and recommendations of this project, future researchers can next determine how and when to conserve water resources at the station in order to sustain ecological integrity of the streams.

Conservation of water resources is extremely important at the research station, for countless other species rely on the same water sources that the TCU researchers could use. Water conservation is an important educational tool for teaching the impacts that they will have on the streams in many ways, especially relating to anthropogenic effects on water quality and availability.

Negative anthropogenic effects on the station's water resources can be prevented by using this data along with the EPA's (2006) stream monitoring program for stream protection. Prevention of stream degradation is most attainable if baseline properties are measured when human influence is at a minimum.

Current water quality and availability during a time of minimal human influence has been presented here, providing baseline hydrological data for two stream segments during a dry season at the research station. This snapshot of the local hydrology can provide insight for developing a sustainable management plan. The baseline data specifically includes physical stream descriptions, water quality measurements, sediment transport measurements, invertebrate samples, and maps, all to be integrated with future studies for a more comprehensive understanding of the watershed.

Continuing watershed study will be very beneficial for maintaining water resources at the research station, but this project cannot be considered a complete sustainable water management program. Such a plan would be a more formal document including a description of stakeholders, a definition of the minimally acceptable stream health criteria, a management framework or matrix, a predictive model, the accepted stream monitoring protocol, and more.

In fact, it would be very beneficial to not only acquire more data over the years to come but also to measure more frequently. This project reports data taken every three to six hours, but because automatic data loggers are being used, stream assessment can be continued, ideally with logging at the recommended rate of once an hour. Also, it would be beneficial to upload data from the WQMS's once in the dry season and once in the rainy season to compare seasonal differences because it is likely that these parameters (stage, conductivity, water temperature, and percent saturation) vary seasonally.

It is also recommended that macroinvertebrates be sampled when researchers are at the station at an interval that does not threaten the insects' populations (Environmental Protection Agency, 2006). Because macroinvertebrates were sampled in January for this project, for consistency it is recommended that sampling continue in January at the same locations. January marks the third month of the dry season, so it is also recommended to sample the sites again in July, the third month of the rainy season, for comparison. Any severe decrease in species' populations or changes in average score per taxon should be closely examined.

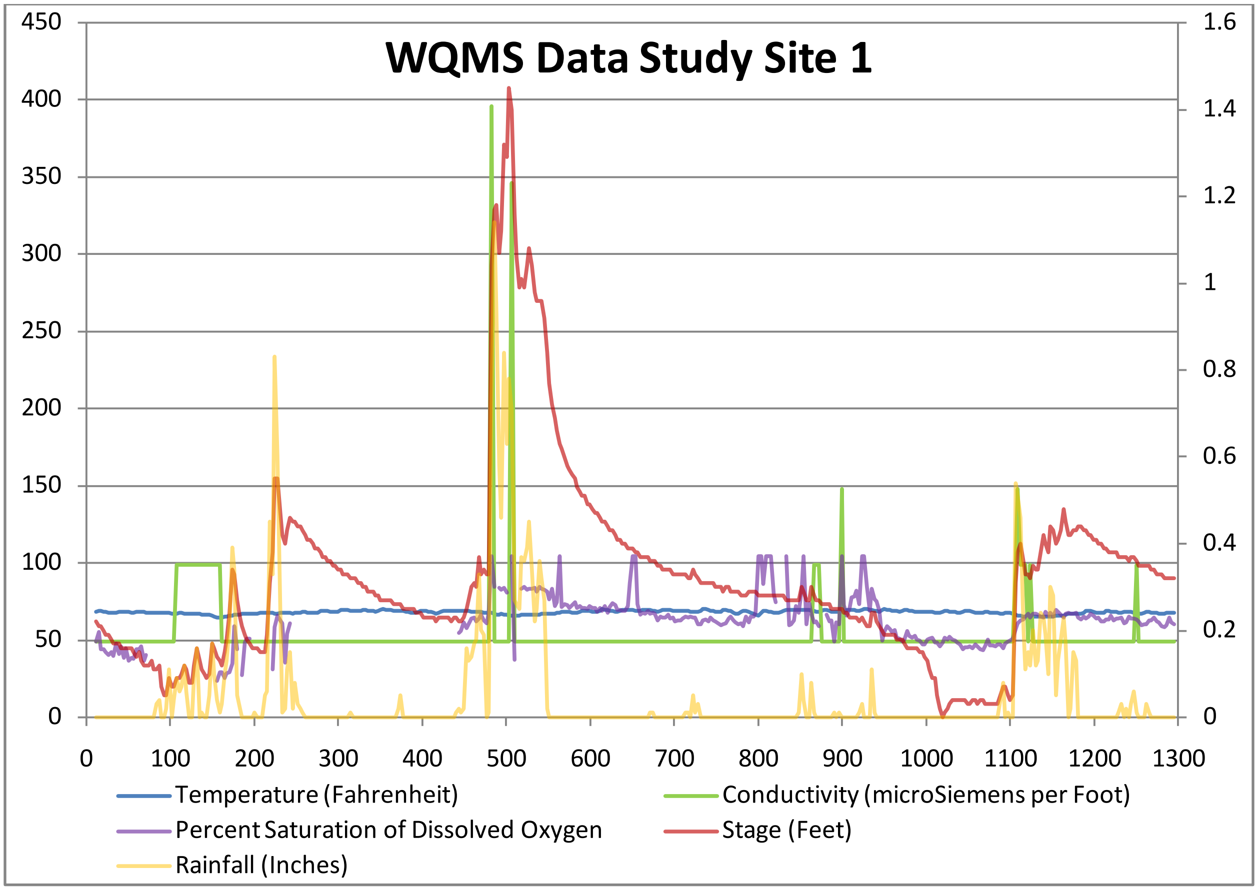
Several conclusions can be made from the data logged during this project. For one, the stage records indicated that within the three-hour measurement resolution the streams are currently responding very similarly to storm events even though the concepts of forest hydrology predict greater contrast. In the end, this unexpected similar behavior should be monitored very closely. It is likely that there will be a significant change in stream response at study site 2 due to ongoing soil compaction which could reduce soil infiltration rates and increase rainfall runoff rates. Although these streams have similar stage responses to rainfall, they differ in terms of chemical properties. The stage response findings do not indicate that study site 2 has been negatively impacted by grazing, but the chemical data shows a significant difference. As predicted, the conductivity and percent oxygen saturation findings indicate a more pristine stream at study site 1 and an adversely impacted stream at study site 2. The aquatic macroinvertebrates do not support the hypothesis of a difference in stream quality caused by grazing impacts, but it does not refute this hypothesis.

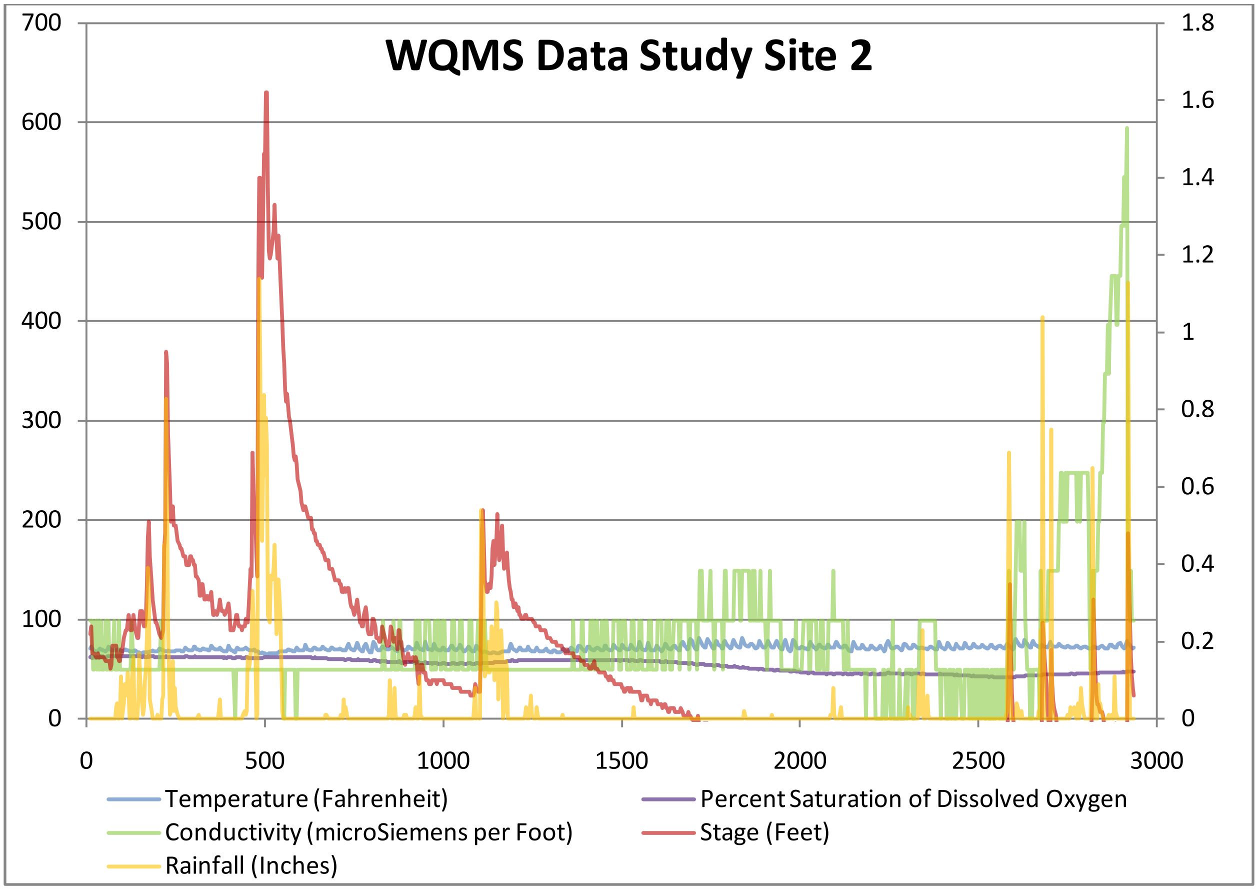
Even though the water quality at study site 2 is lower than that of study site 1, both the cross-sections and velocity readings show that more water is available at study site 2. This may pose a serious problem because most of the water to be used by TCU students will come from the stream with less water (study site 1). Based on the findings of this project, study site 1 is much more vulnerable to degradation from water extraction than study site 2. This poses the question: can there be sustainable water management at study site 1? The answer is yes. As long as water use is less than stream discharge rate and does not degrade biological conditions, responsible water use can be sustainable. Water use can be sustainable at both sites so long as careful monitoring continues as a result of the objectives and findings of this project.

This project shows how much there is to be learned from the research station’s stream network. Hopefully TCU researchers will realize their ‘awareness of ignorance,’ that will spawn the ‘acquisition of learning’ in continuing watershed study that produces an integrated sustainable water management plan.

APPENDIX

CUMULATIVE DATA FOR STUDY SITES




WQMS Data Study Site 2
700
600
500
400
300
200
100
0
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
500
1000
1500
2000
2500
3000
Temperature (Fahrenheit)
Percent Saturation of Dissolved Oxygen
Conductivity (microSiemens per Foot)
Stage (Feet)
Rainfall (Inches)

	Coordinates (Degrees, Decimal Minutes)	**Stream Order**	Flow Regime	**Substrate**	**Riffles Present?**	**Organic Matter?**	**Basin Area (mi²)**
Study Site 1	W -84°33.305028’ N 10°15.117873’	1	Perennial	Boulder	Yes	No	0.15
Study Site 2	W -84°33.680983’ N 10°14.862319’	2	Perennial	Boulder	Yes	No	0.75

	WQMS Data Date Duration	**Total Rainfall (in)**	**Largest Stage Change (ft)**	**Average Temp. (°F)**	**Average % Saturation of D.O.**	**Average Conductivity (µS/ft)**	**Average Turbidity (NTU’s)**	**pH on 05/19 /09**
Study Site 1	01/16/09 03/12/09	23.99	1.94	68.3	62.3	54.56	69.9	5.52
Study Site 2	01/16/09 05/18/09	31.18	1.62	71.5	54.35	78.64	N/A	5.37

	Discharge Rate (ft^3/s) in January 2009	**Discharge Rate (ft^3/s) in May 2009**	**Width (ft)**	**Average Depth (ft)**	**Simpson’s Index Score**	**BWMP Score**
Study Site 1	0.042	0.027	9.35	0.47	0.32	4.75
Study Site 2	5.31	5.41	13.23	0.56	0.33	6.06

REFERENCES

Armitage, P., Moss, D., Wright, J., & Furse, M. (1983). The performance of a new biological water quality score based on macroinvertebrates over a wide range of unpolluted running-water sites. *Water Research , 17*, 333-347.

Baron, J. S., Poff, L. N., Angermeier, P. L., Dahm, C. N., Gleick, P. H., Hairston, N. G., et al. (2002). Meeting ecological and societal needs for freshwater. *Ecological Applications , 12* (5), 1247-1260.

Brierley, G. J., & Fryirs, K. A. (2005). *Geomorphology and River Management.* Oxford, England: Blackwell Publishing.

Brooks, K. N., Ffolliott, P. F., Gregersen, H. M., & DeBano, L. F. (1997). *Hydrology and the Management of Watersheds* (2nd ed.). Ames, IA: Iowa State University Press.

Burt, T. P., & Slattery, M. C. (2005). Land use and land cover effects on runoff processes: agricultural effects. (M. Anderson, & J. McDonnell, Eds.) *Encyclopedia of Hydrological Sciences* , pp. (1805-1812).

Cary Institute of Ecosystem Studies. (2008). *Dissolved Oxygen*. Retrieved March 14, 2009, from Changing Hudson Project: http://www.ecostudies.org/chp_measurement_tools.html

Chang, M. (2006). *Forest Hydrology: An Introduction to Water and Forests.* Boca Raton, FL: Taylor & Francis Group.

Cole-Christensen, D. (1997). *A Place in the Rain Forest.* Austin, TX: University of Texas Press.

Davis-Stamatis, A. (2009, May). (A. Schlipmann, Interviewer)

Dingman, S. L. (2002). *Physical Hydrology* (2nd ed.). Long Grove, IL: Waveland Press, Inc.

Environmental Protection Agency. (2006, November 30). *Volunteer Stream Monitoring: A Methods Manual.* Retrieved May 11, 2009, from United States Environmental Protection Agency: http://www.epa.gov/volunteer/stream/

Fenoglio, S., Badino, G., & Bona, F. (2002). Benthic macroinvertebrate communities as indicators of river environment quality: an experience in Nicaragua. *Revista de Biologia Tropical , 50* (3), 1125-1131.

Folke, C. (2003). Freshwater for resilience: a shift in thinking. *Philosophical Transactions: Biological Sciences , 358* (1440), 2027-2036.

Gleick, P. H. (1998). Water in crisis: paths to sustainable water use. *Ecological Applications , 8* (3), 571-579.

Gleick, P. H., Loh, P., Gomez, S. V., & Morrison, J. (1995). *California water 2020: a sustainable vision.* Oakland: Pacific Institute for Studies in Development, Environment, and Security.

Gordon, N. D., McMahon, T. A., & Finlayson, B. L. (1992). *Stream Hydrology.* West Sussex, England: John Wiley & Sons Ltd.

Griffith, J. A., Martinko, E. A., Whistler, J. L., & Price, K. P. (2002). Interrelationships among landscapes, NDVI, and stream water quality in the U.S. Central Plains. *Ecological Applications , 12* (6), 1702-1718.

Hart, B. T., Maher, W., Batley, G., McKelvie, I., Kelly, M., Campbell, I., et al. (2002). Water. In F. R. Burden, *Environmental Monitoring Handbook* (pp. 19-238). New York, NY: McGraw-Hill.

Heartsill-Scalley, T., & Aide, T. (2003). Riparian vegetation and stream condition in a tropical agriculture-secondary forest mosaic. *Ecological Applications , 13* (1), 225-234.

Hilsenhoff, W. (1988). Rapid field assessment of organic pollution with a family-level biotic index. *The North American Benthological Society , 7* (1), 65-68.

Holland, M. M., Blood, E. R., & Shaffer, L. R. (2003). *Achieving Sustainable Freshwater Systems.* Washington, DC: Island Press.

ISRIC- World Soil Information. (2009, May 15). *World Soil Library and Maps.* Retrieved May 19, 2009, from ISRIC- World Soil Information: http://www.isric.org

Jackson, R. B., Carpenter, S. R., Dahm, C. M., McKnight, D. M., Naiman, R. J., Postel, S. L., et al. (2001). Water in a changing world. *Ecological Applications , 11* (4), 1027-1045.

Karr, J. R., & Chu, E. W. (1999). *Restoring Life in Running Waters.* Washington, D.C.: Island Press.

Leemans, R., & Cramer, W. (1991). *The IIASA database for mean monthly values ot temperature, precipitation and cloudiness on a global terrestrial grid. IIASA Research Report RR-91-18.* Laxenburg: International Institute of Applied Systems Analyses.

Merritt, R., Cummins, K., & Berg, M. (Eds.). (2008). *An Introduction to the Aquatic Insects of North America* (4th ed.). Dubuque, IA: Kendall/ Hunt Publishing Company.

Meyer, J. L. (1997). Stream health: incorporating the human dimension to advance stream ecology. *Journal of the North American Benthological Society , 16* (2), 439-447.

Nadkarni, N., & Wheelwright, N. (1999). *Monteverde: Ecology and Conservation of a Tropical Cloud Forest.* New York: Oxford University Press.

Omni Maps. (2009). *Omni Resources Sample Directory.* Retrieved May 9, 2009, from OmniMap.com: www.omnimap.com

Orozco, G. (2008, May). (A. Schlipmann, Interviewer)

Pereira, H. C. (1973). *Land Use and Water Resources in Temperate and Tropical Climates.* London, England: Cambridge University Press.

Pielou, E. (1969). *An Introduction to Mathematical Ecology.* New York, NY: Wiley.

Revenga, C., Campbell, I., Abell, R., de Villiers, P., & Bryer, M. (2005). Prospects for monitoring freshwater ecosystems towards the 2010 targets. *Philosophical Transactions: Biological Sciences , 360* (1454), 397-413.

Richter, B. D., Mathews, R., Harrison, D. L., & Wigington, R. (2003). Ecologically sustainable water management: managing river flows for ecological integrity. *Ecological Applications , 13* (1), 206-224.

Rogers, K. H., & Bestbier, R. (1997). *Development of a protocol for the definition of the desired state of riverine systems in South Africa.* Pretoria: Department of Environmental Affairs and Tourism.

Rojas, R. E. (1998, November). *Adopt-a-Stream: Environmental Education at Las Cruces (or Changing Students' Attitudes Toward Polluted Rivers)*. Retrieved May 12, 2009, from Amigos Newsletter: http://www.ots.duke.edu/en/amigos/50/adopt.htm

Rosenberg, D. M., & Resh, V. H. (1993). *Freshwater Biomonitoring and Benthic Macroinvertebrates.* New York, NY: Chapman and Hall.

Schaetzl, R., & Anderson, S. (2005). *Soils: Genesis and Geomorphology.* New York: Cambridge University Press.

Simpson, E. (1949). Measurement of diversity. *Nature , 163* (4148), p. 688.

Slattery, M. C., Gares, P. A., & Phillips, J. D. (2006). Multiple modes of storm runoff generation in a North Carolina coastal plain watershed. *Hydrological Processes , 20* (14), 2953-2969.

Steedman, R. J. (1994). Ecosystem health as a management goal. *Journal of the North American Benthological Society , 13* (4), 605-610.

Strahler, A. (1952). Hypsometric (area-altitude) analysis of erosional topography. *Bulletin of the Geological Society of America , 63* (11), pp. 1117-1142.

The President of the Republic Minister of Atmosphere and Energy and the Health Minister. (2007, September 17). *Decretos.* Retrieved May 5, 2009, from La Gaceta Digital: http://www.gaceta.go.cr/pub/2009/07/01/

Thomas, M. F. (1994). *Geomorphology in the Tropics.* West Sussex: John Wiley & Sons Ltd.

Thompson, S. H. (1999). *Water Use, Management, and Planning in the United States.* San Diego: Academic Press.

Thorne, C. R. (1998). *Stream Reconnaissance Handbook.* West Sussex: John Wiley & Sons Ltd.

U.S. Geological Survey. (2001). *Geographic Names Information System.* Reston, VA: U.S. Geological Survey.

Wallace, J. S., Acreman, M., & Sullivan, C. (2003). The sharing of water between society and ecosystems: from conflict to catchment-based co-management. *Philosophical Transactions: Biological Sciences , 358* (1440), 2011-2026.

Washington Suburban Sanitary Commission. (2009). *Water Usage*. Retrieved March 15, 2009, from Washington Suburban Sanitary Commission: http://www.wsscwater.com/service/WaterUsageChart.cfm

Wirthmann, A. (1994). *Geomorphology of the Tropics.* Darmstadt: Wissenschaftliche Buchgesellschaft.

VITA

Abby Schlipmann, born in Quincy, IL on June 10, 1982, is the daughter of John and Jacqueline Schlipmann. She attended Quincy Senior High School and then went to University of Illinois Urbana-Champaign to receive her Bachelor of Science degree in Horticulture in 2004.

At University of Illinois, Abby was a member of the Horticulture Club for which she displayed gardens at a popular parents' weekend garden show. She was also involved in the University of Illinois Student Institute of Floral Design, acting as president for one year. Abby competed in several state-wide floral competitions, receiving honorary acknowledgements. She was employed by the university's floral department for most of her college career, and usually held two or more part-time jobs working at restaurants and garden centers. During her college career, she was inducted into a scholastic fraternity, Pi Alpha Xi, for Natural Resources and Environmental Science students. Throughout college she was awarded several scholastic scholarships.

After college, Abby worked as a floral department manager at a local retail chain where she was highly reputable for her wedding work. In September 2006, Abby decided to join Americorps to volunteer in an environmental program, where she worked for the Maryland State Parks in several conservation projects. During this time, she spent time volunteering for a park that focused on outdoor activities for the disabled.

In August 2007, Abby moved to Fort Worth to attend graduate school at Texas Christian University to pursue her Master of Science degree in Environmental Science. While at TCU she worked as a TA in Principles of Environmental Science, co-authored a revised version of an environmental science lab manual, was selected to serve on an important climate change committee, and was a member in planning a citywide conference based on the future of our urban environment.

ABSTRACT

BASELINE HYDROLOGY FOR A LONG-TERM STREAM MONITORING PROGRAM: A FIRST STEP TOWARD SUSTAINABLE WATER MANAGEMENT AT THE TEXAS CHRISTIAN UNIVERSITY TROPICAL RESEARCH STATION

by Abby Schlipmann, B.S., 2004
Department of Environmental Science
Texas Christian University

Thesis Advisor: Dr. Michael Slattery, Professor of Environmental Science, Department Chair

With Texas Christian University's recent acquirement of a tropical research station in Costa Rica, plans for the station's infrastructure as well as research structure are being made. Part of this plan is to make the research station sustainable. Because the research station relies on local streams as a water source, a sustainable water management plan is essential. While such a plan may take years to develop, a foundation for sustainable water use can be made by providing baseline data and suggesting an ongoing stream monitoring program. This project provides a baseline by measuring the (i) chemical, (ii) biological, and (iii) physical properties of two stream sites at the research station. The sites, assessed *a priori* as either pristine or impacted by grazing activity, were then analyzed based on the three parameters. The baseline data of this project also includes maps generated in geographic information systems, which are important in analyzing the regional basin. Based on the type of measurements taken in this project and the foreseen use of the research station, this paper suggests an appropriate stream monitoring program after consideration of three successful monitoring programs.