Sessom Creek Sediment Export Study

EAHCP PROPOSAL NO. 160-17-TESS

FINAL REPORT

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Executive Summary

Purpose

This report presents the findings of a two-year project with the purpose of quantifying concentrations and loads of non-point-source (NPS) pollutants (suspended sediment, total and dissolved nutrients (Phosphorus and Nitrogen), and bacteria) into the upper San Marcos River during storm flows in the Sessom Creek watershed (EAA Study No. 160-17-TESS).

Problem Statement and Scope

The Sessom Creek watershed is located at the headwaters of the San Marcos River, is highly urbanized, steep, and contains almost no stormwater management infrastructure. As a result, stormwater and NPS contaminants are quickly transported into the San Marcos River where they pose a threat to water quality and critical habitat for several Federally Threatened, Endangered, or petitioned species. The Edwards Aquifer Habitat Conservation Plan is tasked with ensuring healthy habitat for these species. Efforts to protect or restore habitat require quantitative data. A primary objective of this project was to provide these data, analysis of the data, and to use the data to build models that might reveal more about NPS loads and the hydrologic zones in the watershed where the largest proportions of NPS loads are derived. The study area was restricted to inside the Sessom Creek watershed, and the project duration was 22-months, beginning in March, 2018 and ending in December 2019.

Three tasks were performed to accomplish the purpose of this work: 1) Collect data on sediment and constituent loading; 2) Calculate sediment/constituent loading curves, and; 3) Analyze data and examine factors contributing to sediment export.

Findings

Twelve storm events were sampled in 2018, during which more than 300 stormwater samples were collected; each of which was analyzed for a suite of NPS constituents. Analytical results, in combination with continuous turbidity and discharge data, were used to develop continuous discharge-constituent rating curves for Total Suspended Sediments (TSS) and Total Phosphorous (TP), and to model total export of TSS and TP over a 14-month period using LOADEST. Continuous turbidity and discharge were both measured near the bottom of the watershed.

Total loads for NPS constituents in each of the 12 sampled storm events were also calculated by integrating measured concentrations across discharge in each event.

Large differences in storm events, combined with an absence of statistically-significant relationships between discharge and other analyzed NPS constituents (such as TN), prevented useful continuous rating curves from being constructed for those constituents. However, Total Loads and Event Mean Concentrations (EMC) were useful for understanding some of the factors that contribute to variability in exported loads on a whole-storm basis. Several constituents had simple linear relationships with during-event and/or antecedent environmental conditions, including antecedent potential evapotranspiration, rainfall amount, rainfall duration, and peak discharge. Although these relationships require additional data to be collected, other than continuous discharge and turbidity, they do suggest that reasonable estimates of loads and/or EMCs of constituents such as TN, NH_4^+, and NO_3^- might be obtained with minimal monitoring effort or expense in the future.

Bacteria loads being transported from Sessom Creek to the San Marcos River were very high during storm events, and all samples tested positive for Total Coliform. *E. coli* (which is one component of Total Coliform) was present in all samples, and exceeded concentrations of 120,000 MPN/100 mL in some first-flush and peak flow samples. All samples exceeded US EPA recreational limits for *E. coli* concentrations. Actual bacterial loads could not be calculated due to analytical methods.

The estimated sediment (TSS) load during the 14-month monitoring period, using the LOADEST model based on discharge, was 107,520 kg, and the estimated total phosphorus load based on discharge for the same period was 298 kg. Using the USGS Turbidity Spreadsheet Tool, the estimated sediment load for the 14-month monitoring period was 65,799 kg. The differences between models is due to uncertainties and the different methods used in each model.

The LOADEST results are supported by total loads calculated for TSS and TP that are derived from direct analyses of TSS and TP in samples collected across each of 12 storm events between March and September of 2018. Calculated loads of TSS and TP, using measured discharge and concentrations in the discrete samples integrated across the 12 storm events, were 65,598 kg, and 107 kg, respectively.

Total measured loads of other NPS constituents in the 12 sampled storm events were: VSS = 11,863 kg, NVSS = 53,735 kg, TN = 336 kg, NH_4^+-N = 21 kg, NO_3^--N = 118 kg, and SRP = 21 kg.

A proposed stormwater detention pond BMP in the Windmill tributary was assessed using SWAT modelling. Although it was effective in attenuating peak flows in the tributary during large storms, the relatively insignificant contribution of the Windmill tributary to the main channel in terms of total flow rate and sediment yield resulted in a marginal reduction in sediment yield at the watershed outlet. Specifically, the model suggests that only a 13.5% reduction of sediment yield could be expected at the Sessom Creek watershed outlet.

Variability between storm events, and a lack of clear relationships between most NPS constituents (TN, SRP, NH_4^+-N, NO_3^--N, NVSS, and VSS) and discharge, prevented model construction for estimating each of these parameters. However, relationships between Event Mean Concentrations (EMCs) and other environmental or NPS parameters do suggest that simple linear models may be useful for estimating loads of other nutrients (e.g., NH_4^+-N *vs.* 2-week antecedent potential evapotranspiration). Use of these relationships in future monitoring efforts will require continuous monitoring of precipitation and temperature data in the watershed, in addition to continuous discharge and turbidity, but they may be the simplest method for estimating event-based loads of these parameters. While the required parameters are relatively inexpensive to measure, maintenance of the related equipment and subsequent data processing can require non-trivial amounts of time to accomplish.

Hysteresis analysis of the relationships between turbidity-derived TSS and discharge in 42 storm events suggests that bank erosion, distant sediment sources, dry conditions, and upstream tributaries contributed the bulk of the sediment load in slightly more than half of all events. In most of the remaining events, mobilization of "in-channel" sediment sources that appear before the peak flow is an important source. However, because much of the watershed is comprised of impervious surfaces, much of this "in channel" source may be comprised of fine organic debris collected on streets, parking lots, and roofs, and which is quickly mobilized and transported during the first-flush. Evidence supporting this is in visual color differences observed in collected water quality samples (the first 1-3 samples are often different in color and higher in TSS concentration than later samples), and a generally higher VSS proportion in the first samples. Higher VSS suggests that fine organic sediments accumulate on impervious surfaces and are quickly being flushed off before higher velocities and shear-stresses begin eroding the actual channel materials. These hypotheses are supported by observational evidence in the field during storm events.

Summary Results

- LOADEST- modeled TSS and TP loads during a 14-month period were 107,520 kg and 298 kg, respectively.
- Loads of TSS and TP measured in 12 storm events were 65,598 kg, and 107 kg, respectively.
- A SWAT assessment of a BMP in the Windmill tributary suggests the marginal sediment load reductions will be attained at the outlet of Sessom Creek.
- All stormwater samples contained very high concentrations of *E. coli* that exceed US EPA recreational contact limits.
- Simple linear models between EMCs of some NPS constituents and environmental and/or other NPS parameters may be a useful method for estimating loads.
- Hysteresis analyses suggest that sediments transported during small storm events and during the first-flush may be largely derived from impervious surfaces.

BACKGROUND AND SIGNIFICANCE

In 2013, the United States Fish and Wildlife Service (USFWS) issued an Incidental Take Permit (ITP) to the Edwards Aquifer Authority, Texas State University (TXSTATE), the City of San Marcos, the City of New Braunfels, and the San Antonio Water System (SAWS) for the use of the Edwards Aquifer and its spring-fed ecosystems. The ITP is maintained through the Edwards Aquifer Habitat Conservation Plan (EAHCP). As part of the first phase of the EAHCP (Phase 1), applied research projects examining the ecology of spring-associated ecosystems and the organisms covered by the ITP have been conducted alongside ecological modeling efforts. Organisms covered by the ITP are the fountain darter (*Etheostoma fonticola*), Texas wild rice (*Zizania texana*), the Comal Springs riffle beetle (*Heterelmis comalensis*), the San Marcos salamander (*Eurycea nana*), the Texas blind salamander (*Eurycea rathbuni*), the Peck's Cave amphipod (*Stygobromus pecki*), the Comal Springs dryopid beetle (*Strygoparnus comalensis*), Edwards Aquifer diving beetle (*Haideoporus texanus*), Comal Springs salamander (*Eurycea* sp.), the Texas troglobitic water slater (*Lirceolus smithii*), and the San Marcos gambusia (*Gambusia georgei*; assumed extinct). Much of the prior applied research effort has focused on determining the effects of temperature and dissolved oxygen changes on these organisms, which can result from low-flow conditions in the Comal and San Marcos Springs ecosystems. However, there is also concern about the effects of stormwater-derived sediment and nutrient loads on the above listed species; especially Texas wild rice, which is endemic to the San Marcos River.

This document is the Final Report for a study that quantified suspended sediment, total and dissolved nutrient (Phosphorus and Nitrogen), and bacteria concentrations and loads into the San Marcos River during storm flows in the Sessom Creek watershed (EAA Study No. 160-17-TESS).

INTRODUCTION AND LITERATURE REVIEW

The Sessom Creek watershed

In the larger Upper San Marcos River watershed, there are 4 sub-watersheds of significant size: Sink Creek, Purgatory Creek, Willow Creek, and Sessom Creek (Figure 1). Sessom Creek is the only one of the four which is entirely contained in the limits of the City of San Marcos, and which is wholly on the transition zone between the recharge and confined zones of the Edwards Aquifer (Blome et al, 2005). Because of its physical characteristics (described below) and proximity to the headwaters of the river, the Sessom Creek sub-watershed has been identified as an area where future changes in watershed management and implementation of better management practices (BMPs) could reduce detrimental effects of stormwaters on the San Marcos River. In particular, stormwater loads of sediment and nutrients result in negative impacts to aquatic ecosystem health and river recreation.

During non-storm conditions, no surface waters flow in the Sessom Creek watershed, except in a short reach immediately above the confluence with the San Marcos River where Sessom Creek discharges high quality water into the San Marcos River. This reach has baseflows between 1-4 cfs (unpublished data collected by PIs Schwartz and Nowlin) that are derived from a cluster of small springs emanating from the Edwards Aquifer where the Sessom Creek channel crosses the northeastern end of the Hueco Springs Fault. This fault delineates the local boundary between the Recharge/Transition and Artesian Zones in the Edwards Aquifer. The two known endangered aquifer species found in Sessom Creek are found in or near these springs (the Texas blind salamander and the Comal Springs dryopid beetle), but there are at least 15 additional aquifer-endemic species found in these springs.

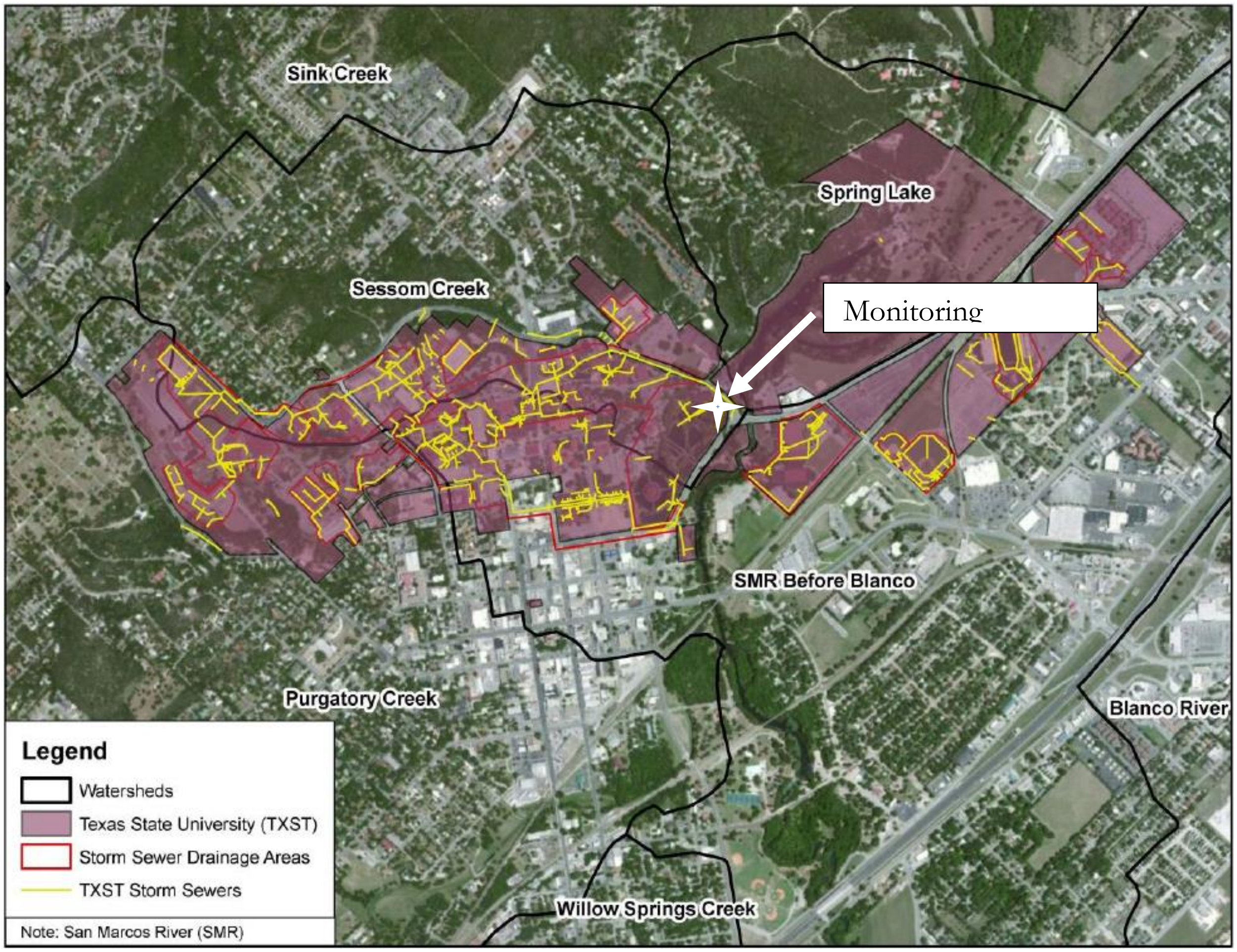

Figure 1. Sessom Creek watershed boundaries and surrounding area.
Includes proposed sampling and monitoring location at the downstream end of Sessom Creek. (Figure modified from John Gleason LLC, 2017).

Stormflow conditions are quite different from those encountered during baseflows. Stormflows result in high concentrations of suspended sediments, particulate matter, dissolved nutrients, and transport of bed-sediments. Previous work has documented how sediment transport and deposition alters bed and channel morphology (Earl and Wood, 2002; Engel and Curran, 2006), and negatively affects stands of Texas wild rice in the San Marcos River near the confluence of Sessom Creek (John Gleason LLC, 2017; White et al, 2006; Griffin, 2006). In lower-velocity impounded reaches of the river (e.g., behind Rio Vista and Capes Dams) suspended sediment also settles onto the stream bed and aquatic vegetation and increased turbidity affects light penetration; both of which can negatively affect aquatic habitat quality and growth of Texas wild rice. A portion of previous work under the EAHCP has targeted removal of both coarse and fine sediments from specific areas in the river channel; at least some of which is derived from Sessom Creek.

Although Sessom Creek is the smallest of four sub-watersheds in the Upper San Marcos River, stormflows from this sub-basin contribute a disproportionate amount of sediment to the headwaters of the San Marcos river system during storm events. This is due to a combination of factors including: 1) high impervious cover and near-complete urbanization in the subwatershed, 2) an absence of effective BMPs in place to retain or detain stormwaters, 3) a highly channelized drainage network with limited riparian zone, 4) portions of the watershed that contain highly erodible geologic materials, and 5) frequent intense and/or large precipitation events common in central TX, in an area also known as 'Flash Flood Alley'. Combined, these factors result in rapid and frequent movement and transport of sediments from the Sessom Creek watershed into the Upper San Marcos River. Because of all the factors described above, Sessom Creek responds rapidly to even small storm events, and as a result, each event transports sediment and other contaminants from the urban environment into the San Marcos River.

The Edwards Aquifer Recovery and Implementation Plan (EAHCP) specifically discusses the impacts of the disproportionately large sediment load being contributed to the river system by Sessom Creek (EARIP, 2012). To date, a detailed understanding of the controls on the amounts and timing of sediment transport, especially fine suspended sediment, from Sessom Creek into the San Marcos River has not been obtained. Prior research in Sessom Creek by the PIs and others highlights extreme variability in Total Suspended Sediment (TSS) loads and type of sediment (i.e., non-volatile suspended sediment (inorganic NVSS) *vs* volatile suspended sediment (organic VSS) *vs* nutrients), and preliminary results suggest that this variability is due to several factors including: antecedent environmental conditions, rainfall intensity/amount, and presence of construction activity in the watershed. In addition, source regions for sediments not associated with construction activity are not well constrained. Construction activity as a major source of sediment was also highlighted by Earl and Wood (2002).

The EAHCP (EARIP, 2012) states that "Sessom Creek is exhibiting a high rate of stream erosion, resulting in excessive sedimentation in the San Marcos River. Much of the stream erosion can be attributed to changes in watershed hydrology due to development and impervious cover. To bring this watershed closer to a state of equilibrium, the WQPP recommends that the City and the University implement projects both within the channel and throughout the watershed." Recommended actions include: stabilize the banks; restore the riparian landscape; retrofit projects that incorporate extended detention in order to reduce he impacts of existing development, and; extended detention ("stream protection") requirements for new development and redevelopment.

To maximize the beneficial effects and minimize costs, a more detailed understanding of Sessom Creek erosion is occurring is required. <u>Thus, the goals of this proposed research were to: 1) collect data on sediment and nutrient (total nitrogen and total phosphorus) loading from Sessom Creek, 2) calculate sediment and nutrient loading curves from Sessom Creek, and 3) conduct data analysis to better understand the physical factors contributing to sediment and nutrient exports from the Sessom Creek watershed</u>.

CONCEPTUAL FOUNDATION, EXPERIMENTAL DESIGN, AND METHODS

Sessom Creek was monitored continuously for precipitation, discharge, and turbidity between 1 Jan 2018 and 28 February 2019. Continuous precipitation and discharge time series data were obtained from NOAA and private sources (i.e., Weather Underground). Continuous turbidity time series data and storm runoff water quality data and samples were collected by Texas State University. Samples were collected to measure water quality parameters over a 10-month period between 27 March 2018 and 7 December 2018, during which time 14 individual storm events were monitored and sampled. Constituent loading was estimated for the entire 14-month period monitoring period using continuous time series data coupled with water quality data obtained from the discrete samples.

Sample collection

An automated ISCO sampler was used to collect time-based stormwater runoff samples during 14 storm events when water level at the Sessom Creek sampling point exceeded 5 cm (0.16 ft) above non-storm event flow conditions; equivalent to discharge exceeding 0.1 m^3/s (3.5 ft^3/s). Historic observations have shown that the watershed produces rapid response runoff events of short duration. Due to this behavior, a non-uniform sampling interval protocol was used to ensure adequate collection of "first flush" constituents during peak discharges. The sampler was triggered by a liquid-level sensor set ~5 cm above the creek's non-stormwater level. Sampling targeted high concentrations of contaminants in the rapidly rising and falling stormwater hydrograph, with fewer samples monitoring the receding limb. A high initial sampling frequency interval of 3 minutes was sequentially increased to 5-minute, 10-minute, and 30-minute intervals over the course of each runoff event. Six samples were collected for each interval. A total of 24 1-L samples, a physical limitation of the automated sampler, were collected per storm event except for Event 1 during which two extra samples were collected during the trailing limb of the hydrograph.

Suspended sediment was determined by the Total Suspended Solids (TSS) method and concentration was reported in milligrams per liter (mg/L). The TSS method was chosen so that storm samples could be sub-sampled and analyzed for multiple constituents. It is known that TSS often underestimates the suspended sediment concentration (SSC) due to particle settling during sub-sampling (Gray et al., 2000). In order to determine the relationship between TSS and SSC in the Sessom Creek Watershed, one sample plus a manually-collected duplicate sample from each of 10 runoff events were processed by both methods and results compared. In addition, two storm events were sampled and used exclusively for TSS/SSC comparison. Average differences were found to be < 1% and TSS was judged to be a reasonable representation of the suspended sediment concentration, without correction.

Analytical methods

Water quality data used in this study were collected between 27 March and 7 December 2018 as part of an assessment of water quality in Sessom Creek, and the associated discharges and loads into the San Marcos River. Continuous time series records of precipitation, discharge, and turbidity were collected for the entire monitoring period from 1 January 2018 to 28 February 2019. These records were standardized and aligned with water quality measurements in order to develop regressions for estimating constituent loads, develop rating curves, and providing calibration information for process modeling using the Soil and Water Analysis Tool (SWAT).

Precipitation data

Precipitation data used in Sessom Creek analysis was obtained from two sources, the National Oceanographic and Atmospheric Administration (NOAA) service and the Weather Underground, an on-line commercial weather service providing private citizen collected real-time weather information. Hourly rainfall estimates from NOAA were generated by a multiple radar multiple sensor (MRMS) process yielding a single, hourly average precipitation value representing the whole watershed. The period of record for this analysis was 1 Jan 2018 to 28 February 2019. This record was used as the primary Sessom Creek precipitation time series data set. One-minute precipitation values were obtained from the Weather Underground, for 12 days during the study period. Daily records were downloaded for days during which individual storms events were monitored for water quality (i.e., events during which automated water samples were collected). Records from Station KTXSANMA24 (i.e., privately owned AcuRite Pro Weather Center), located near the center of the watershed, were downloaded due to their high temporal resolution (1-minute interval data) during monitored runoff events. These data were combined with the lower resolution (60-minute) NOAA data and used for preparing time series required for statistical and process-based SWAT modeling.

Flow data

Discharge was measured by a NOAA non-contact scanning LiDAR gauging station (a Sommer RQ30 instrument installed by the NOAA SSL ANCHOR project) approximately 100m upstream from WQ sampling location. This gauge utilized a variable-rate logging interval. Discharge values < 0.1 m3/s were logged at 10-minute intervals but, when discharge values exceeded 0.1 m3/s, the logging interval increased to 1 minute. A 3 to 5-minute delay in the automated discharge calculation from level measurements was apparent and resulted in occasional gaps in calculated discharge values near the frontend of runoff events.

Turbidity data

Turbidity was measured by two instruments at the water quality sampling point. One of the instruments was installed and is maintained as a real-time data collection station by the EAA (instrument: Eureka Manta 3.5). Due to early sporadic issues with data collection on the EAA instrument, we also deployed a YSI YSI 6920-V2 sonde with a 6136 turbidity probe in the same location to ensure a back-up record in case of failure. The primary record (EAA data) was paired with water quality data for all monitored storms except storm 12 when data from a secondary instrument was used due to a gap in the primary record. The primary record initially used a 15-minute logging interval from 3 January 2018 to 25 May 2018 after which it was increased to a 5-minute logging interval for the remainder of the monitoring period. The secondary instrument used a 3-minute logging interval.

Nutrients and Bacteria

Samples were analyzed in the Nowlin-Schwartz Lab at Texas State University for the following water quality parameters: total nitrogen (TN), total phosphorus (TP), soluble reactive phosphorus (SRP), ammonium-nitrogen ($NH4^+$-N), nitrate-nitrogen ($NO3^-$-N), total suspended solids (TSS), non-volatile suspended solids (NVSS), volatile suspended sediments (VSS), Total Coliforms (TC), and *E. coli*.

Samples were processed and analyzed within 24 hours of collection for bacteria and preserved within 48 hours for all other parameters. For analysis of TSS, NVSS, and VSS, a known volume of the homogenized sample was filtered using Pall A/E (1μm nominal pore size) pre-ashed filters. After filtration, filters were dried at 60 °C for 48 h, weighed, combusted at 500 °C for 4 hours, and re-weighed. Mass loss was used to quantify TSS, NVSS, and VSS (Eaton et al., 1995). Filtered samples were used to analyze dissolved nutrients, while total nutrients were measured on unfiltered sample. Both filtered and unfiltered samples were preserved with sulfuric acid (H2SO4) for dissolved and total nutrients respectively. All samples were stored at <4 °C in clean 125 mL HDPE bottles (Eaton et al., 1995) until analysis.

TP and SRP analyses used the ascorbic acid method (Eaton et al., 1995). TN was quantified using second-derivative spectroscopy on a Varian 50S UV/VIS Spectrophotometer (Crumpton et al. 1992). NH4+-N was measured using methods modified from Wetzel and Likens (2000).
TC and E. coli were determined using the Enzyme Substrate Coliform Test (9223 A and B procedures) by doing the multiple-well procedure. Chromogenic substrate (ortho-nitrophenyl-β-D-galactopyranoside (ONPG)-based) was inoculated and mixed into 100 mL of diluted sample (dilutions varied from 1/10 to 1/50), then incubated at 35±0.5 ºC for 24. If the β-D-galactosidase enzyme hydrolyzes the substrate, the medium turns yellow indicating a positive test for TC. The presence of E. coli is determined if fluorescence occurs (Eaton et al., 2005).

Event Mean Concentrations (EMC) and Simple Linear Regressions

Simple Linear Regression Models were used to explore the data and assess possible correlations between Non-Point Source (NPS) loads and Event Mean Concentrations (EMC) and each water quality parameter. Response variables were EMC and total event loads for each of the twelve events, while proposed independent/explanatory variables were: Total rain (Rain), total runoff (RO), duration of the rainfall (Rain dur.), average intensity of the rainfall (Rain Int.), antecedent dry days (ADD), maximum rain intensity (Max RI), maximum discharge rate (Peak Q), accumulated evapotranspiration in the last 8 weeks (ETp8) and in the last 2 weeks (ETp2), accumulated rain in the previous week (Rain 1), and accumulated rain during the 2 previous weeks (Rain 2). Instantaneous discharge is Q in m3/s, and runoff (RO) is the total volume of water transported from Sessom Creek into the San Marcos River during a storm event.

Precipitation, temperature, dew point, and barometric pressure data were obtained from Weather Underground (Sessom Creek KTXSANMA24 Station). Potential evapotranspiration was calculated using the Penman-Monteith equation (Allen, 2005) through the Daily Reference Evapotranspiration Calculator program (Synder & Eching, 2000). Daily solar radiation was obtained from the University of Texas Pan-American Solar Radiation Lab at Austin, TX (Ramos and Andreas, 2011).

Total loads for each storm event were calculated by multiplying Q by the concentration (mass/L) of each variable at a given sampling time, and then integrating these estimates across the hydrograph of a storm event. EMC was determined by dividing the total load by total Q for each storm event. Prior to regression modeling, Pearson correlation matrices were used to test for correlation between NPS loads, EMCs, and explanatory variables. Principal Component Analysis (PCA) was performed to reduce data dimensionality. Both, correlation matrices and PCAs, were performed to understand the degree and significance of correlation between variables and find variables that are most representative of EMCs, loads, and the explanatory variables. Those variables were then prioritized as response variables and predictors in the linear regression models. Additionally, a PCA was performed to visualize the spatial distribution of the data, and to find main loading variables (principal components) that could best summarize the variance of the variables (Balzarine et al., 2008). Thus, key variables selected through the PCA can be used for management purposes to represent NPS pollutants in Sessom Creek. The Pearson coefficient assumes data normality, but data for event loads were skewed left. To correct for this, two outliers were removed for analysis, and permutation tests with 9,999 permutations were used to test the correlation matrix of the response variables. The function used in R was per.relation(x), where "x" would be the correlation between each set of variables. Statistical analyses were performed using R program (R Core Team, 2017).

As statistical outliers, E1 and E10 were not included in the PCA analyses or correlation tables for loads and environmental variables, because they were about one order of magnitude larger than the other events. E1 and 10 caused a deflation of the standard error around the mean, and inflation of the Pearson coefficient; therefore, only the small and medium events were used when predicting loads. Conversely, all 12 events were included for the EMC analysis, because these effects are attenuated when loads are divided by discharge.

Time series preparation

All assembled Sessom Creek data was reviewed, aligned, cleaned, transformed, and rearranged prior to statistical analysis and process-based SWAT modeling. Microsoft Excel was used for simple formatting and visualization. The Python scripting language and functions from the "Pandas" library were used to manipulate and standardize time series data. Pandas, short for "panel data", is a suite of tools developed for manipulating multidimensional structure datasets. It provides functions to aid with missing data, duplicate data, transformations, rearrangement, and more (Mckinney, 2016). Sessom Creek time series data were standardized to common units, time zones, and fixed frequencies through conversions, offsets, and resampling prior to alignment with water quality measurements. Resampling is the process of converting a time series from one frequency to another. Aggregating higher frequency data to a lower frequency is known as down-sampling, while converting from a lower frequency to a higher frequency is called up-sampling. Both processes were used to standardize Sessom Creek time series data required for use with statistical regression development and SWAT modeling efforts.

Raw data for precipitation, flow, and turbidity time series were reported at 1-hour and 1-minute, 10 to 1 minute, and 15, 5 and 3-minute intervals, respectively. Rainfall data was obtained from two sources and followed fixed frequency time intervals. The primary data set used a 1 hour fixed-frequency interval while a secondary data set, collected during 12 monitored runoff events, used a 1-minute fixed-frequency interval. Flow data was collected using a variable time interval, dependent upon discharge rate; when discharge exceeded ~0.1 m3/s, logging was increased from a 10-minute interval to a 1-minute interval. Turbidity data was obtained from two sources using three different time intervals. Between 3 January and 25 May 2018, the primary source used a 15-minute interval which was changed on 25 May to a 5-minute interval which was continued through the end of the monitoring period. Turbidity data from the secondary source utilized a fixed frequency of 3-minutes. Finally, the timestamps among the assembled time series were reported in differing time zones and daylight times requiring alignment to a common time through offsets. The time zone used in this report is Central Standard Time (CST).

The NOAA 1-hour precipitation time series was down-sampled to a 15-minute interval through equal time division (i.e., hourly data value divided by 4) and back filled to the top of the hour. Flow and turbidity time series data sets were first down-sampled to 1-minute intervals, to account for the variable collection scheme, and then forward-filled using interpolation between measurements when no value was available. Each 1-minute interval time series was then up-sampled to common frequencies of 15 minutes, 1-hour, and 1-day using either summation (for precipitation) or averaging (for flow and turbidity), of 15-minuet (rainfall) or 1-minute values (for flow and turbidity). The resulting value for each time interval was labeled at the top of the interval.

The turbidity time series contained several data gaps due to instrumentation issues. Missing data were addressed using one of three approaches. For several, very short intervals (i.e., minutes to several hours), the pandas fill function was used to generate missing values by interpolating between the last known good values. A 1-day gap (Event 12 on 7 September 2018) was filled by substituting data from the secondary source instrument. A large gap of 13 days between 27 March and 8 April 2018 was filled by statistical methods. A relationship between sediment concentration and turbidity was determined from monitored storm events with complete records. This relationship was then used to estimate missing turbidity values for storm events with incomplete records. The pandas up-sampling function, using forward fill and interpolation, was then used to estimate missing turbidity values and produce a continuous turbidity record.

Water quality data (i.e., TSS, Total Phosphorus, Total Nitrogen) were up-sampled from variable, non-uniform time frequencies to uniform 15-minute, 1-hour, and 1-day intervals prior to pairing with flow and turbidity time series required for statistical and SWAT modeling. The interval mean concentration was computed for each constituent. This was determined by calculating the total mass of the constituent divided by the total runoff volume for the interval of interest.

Rainfall, flow, turbidity and water quality data were aligned in time by matching autosampler and turbidity measurement times to the closest-in-time flow measurement and adding a 1-minute lag to account for physical distance between the measurement points. The lag time between discharge measurement location and water quality sampling location was determined by measuring channel geometries and applying the Manning formula to estimate water velocity between the measurement locations.

Hysteresis determination

Hysteresis is the phenomenon in which a physical property proceeds or lags changes in the effect which causes it. Applied to hydrology, it describes the non-linear relationship between discharge and an entrained constituent. Turbidity is often used as a surrogate for suspended sediment concentration as scattering particles which influence turbidity values may include suspended sand, silt and clay, organic matter, and other insoluble particulate substances. Plotting turbidity hysteresis is an effective way to visualize the dynamic response of sediment concentration to changes in flow rate over storm runoff events; cyclic patterns are a common result (Lawler et al. 2006). The size, shape, and direction of the resulting "hysteresis loop" is dependent upon the lag response between the two variables (Lloyd et al., 2016). Hysteresis analysis is useful for characterizing contributing runoff source areas and pathways linking sources with the stream. Five generalized hysteresis types are common: Type 1 – Clockwise, Type 2 – Figure-8, clockwise early in storm reversing to counter-clockwise later, Type 3 – Counterclockwise, Type 4 – counterclockwise early in storm reversing to clockwise later, and Type 5 – straight line (Figure 2).

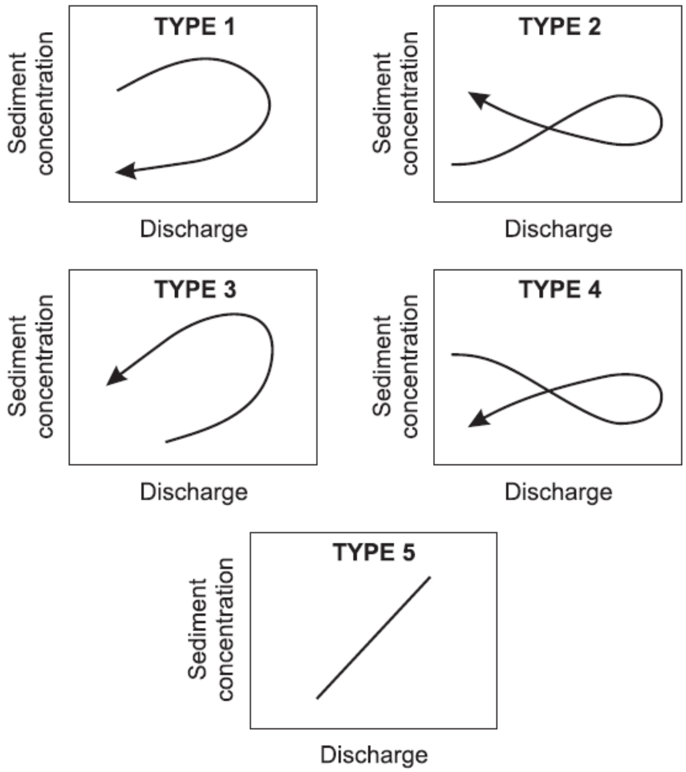

Figure 2. Hysteresis types described by Gellis (2013).
Arrows indicate direction through time. TYPE-1 clockwise, TYPE-2 figure eight, clockwise early in storm reversing to counterclockwise, TYPE-3 counterclockwise, TYPE-4 figure eight, counterclockwise early in storm reversing to clockwise, and TYPE-5 no exhaustion.

Type 1 is explained by "first-flush" mechanisms whereby sediment is rapidly mobilized in the runoff followed by depletion of in-channel or nearby sources. In this case the sediment peak leads the discharge peak. Type 2 is common when the initial contribution comes from the stream bed or banks with delayed contributions from sub-basins. The sediment peak also lags the discharge peak in this case. Type 3 is primarily associated with bank erosion and/or contributions from distant upstream tributaries. Type 4 is seen primarily under dry conditions and Type 5 is suggests an uninterrupted, constantly eroding supply. Causes for each hysteresis type have been described by numerous authors and Gellis (ibid.) provides a concise summary of this literature.

Sessom Creek storm events were defined as increases in discharge above the water quality sampling threshold of 0.1 m^3/s. Storm events were further divided into individual storm peaks defined by either a return to flow $\leq$ 0.1 m^3/s or when discharge began to rise again due to another storm occurrence before the system returned to flow $\leq$0.1 m^3/s. Fifteen-minute discharge and concurrent 15-minute turbidity continuous time series data were used to compute a dimensionless hysteresis index (HI) for each storm peak using methods described by Lloyd et al. (ibid). The resulting index yields a numeric value which can be used to examine individual storm characteristics by describing the width or weight of the difference between the rising and falling limbs of the hydrograph. The data were normalized using the following equations:

$$\text{Normalized } Q_i = Q_i - Q_{\min} / Q_{\max} - Q_{\min}$$

$$\text{Normalized } T_i = T_i - T_{min} / T_{max} - T_{min}$$

Where Q_i / T_i is the discharge/turbidity at timestep i, Q_{min} / T_{min} is the minimum storm parameter value, and Q_{max}/T_{max} is the maximum storm parameter value. Normalized discharge and turbidity values were used to compute the HI based on standardized discharge calculated in 5% increments (i.e., 19 points between 0 and 1. The normalized turbidity values for the rising limb (RL) and falling limb (FL) of the hydrograph were summed and the HI was calculated as:

$$HI = T_{RL\_norm} - T_{FL\_norm}$$

The difference between the turbidity values on the rising and falling limbs of the normalized storm data results in a value between -1 and 1 where 0 represents no hysteretic pattern, positive values indicate Type 1 clockwise hysteresis, and negative values indicate Type 3 counterclockwise hysteresis. Type 2 and 4 figure-of-eight storm responses produce a weighted average of the intervals of discharge measured when the storm was in a clockwise phase and when in a counterclockwise phase. Type 5 storms produce a straight line and are represented by HI values approaching zero. Each peak was plotted and examined visually to confirm the resulting HI value and loop direction as well as to ensure that no individual result was due to a perfectly symmetrical figure 8 event. Using this method, it is possible to produce a value of zero under this condition which could lead the user to believe they had encountered a Type 5 – straight line event. An example of hysteresis plots including raw values, hysteresis loops in measured units and standardized units, and a standardized hysteresis index plot for a typical Sessom Creek storm event are shown in Figure 3.

Load measurement

Suspended sediment, total phosphorus, and total nitrogen loads exported from Sessom Creek Watershed were computed *directly* for monitored storm runoff events by multiplying the measured discharge volume by the individual constituent concentrations and summing the products over the storm interval.

Load estimation based on discharge

Estimations of suspended sediment and total phosphorus exported from Sessom Creek Watershed based on continuous discharge measurements were computed *indirectly* for the 14-month monitoring period using ordinary least squares linear regression. Suspend sediment and total phosphorus loads were estimated as functions of discharge by constructing regressions between paired observations of discharge and the constituent concentration. The US Geological Survey (USGS) Load Estimator (LOADEST) software was used to build the regression models and estimate loads based on the continuous discharge record applied to the regression.

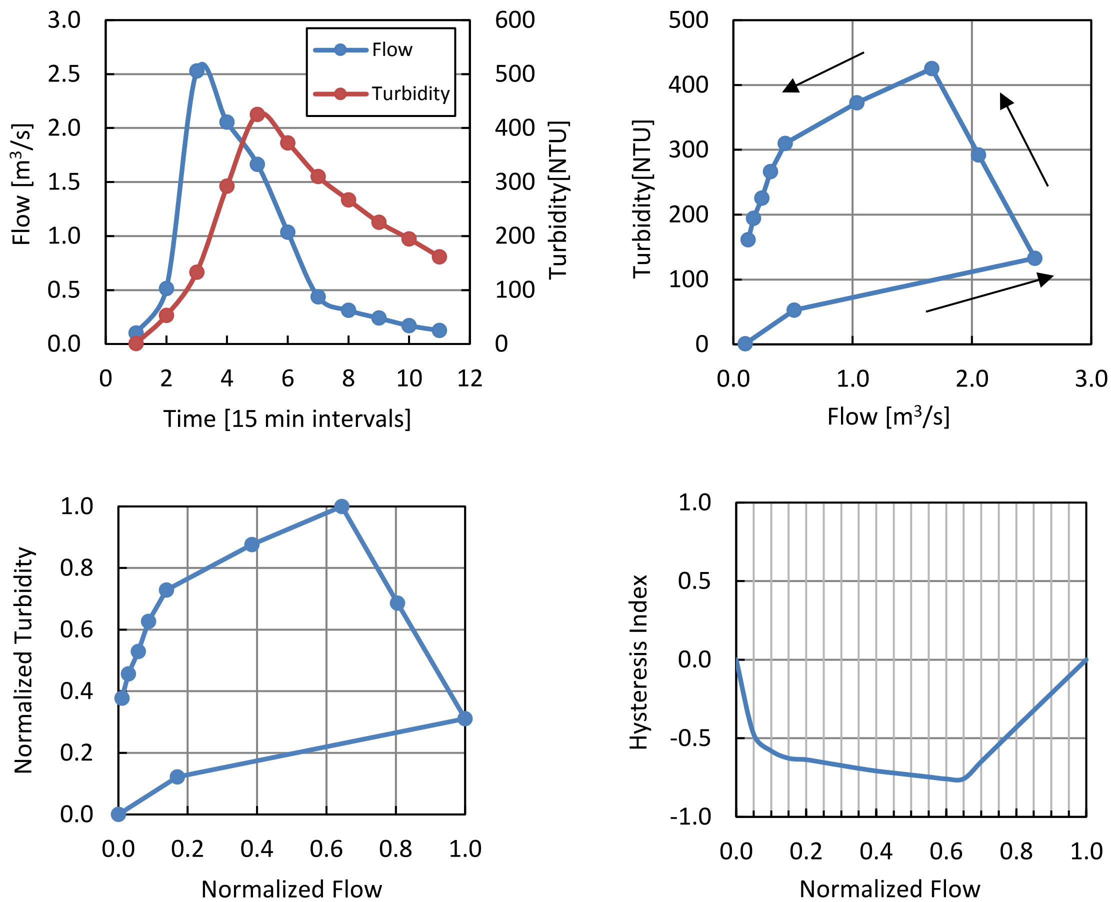

Figure 3. Example sediment hysteresis analysis plots for a Sessom Creek storm runoff. Event occurred on 7 July 2018. a) flow vs time and turbidity vs time illustrating turbidity (i.e., sediment) peak lagging flow peak, b) flow vs turbidity illustrating a counterclockwise "hysteresis loop" in measured units, c) flow vs turbidity illustrating a counterclockwise "hysteresis loop" in standardized units, and d) hysteresis index vs normalized flow at standardized 5% flow intervals. Note all HI values on this plot fall in the negative range indicating a clear and strong Type 3 counterclockwise hysteresis loop.

The USGS LOADEST tool, a Fortran program for estimating constituent loads in streams and rivers, was used for both regression model development and load estimation. The program uses time series of measured stream flow and constituent concentration observations to calibrate a regression model for estimating non-measured constituent loads. LOADEST incorporates three statistical methods that account for retransformation bias, data censoring, and non-normality. These include: Adjusted Maximum Likelihood Estimation (AMLE), Maximum Likelihood Estimation (MLE), and Least Absolute Deviation (LAD) methods. The AMLE and MLE methods are used when the observed versus simulated residuals are normally distributed. AMLE is preferred when censored data are present (i.e., values that are only partially known, for example <1 mg/L). AMLE results are identical to MLE when censored data are not present. The LAD method is preferred when the residuals are not normally distributed. LOADEST software contains several predefined models from which the user can choose or allow automatic selection based on the Akaike Information Criterion (AIC). The AIC procedure applies as many prediction variables as possible while minimizing the standard error of the resulting estimates (Runkel et al., 2004). Outputs include statistical variables and residual components to help determine best model fit. The coefficient of determination (R^2) describes the proportion of variance in measured data explained by the model and ranges from 0 to 1 with values greater than 0.5 generally considered acceptable (Moriasi, 2007). Residual data are used to judge model assumptions of heteroscedasticity (i.e., even distribution or scatter of dependent variables across the range of predictor values) and normality (i.e., the data describe a normal, "bell curve", population). Regression coefficients statistics include standard deviation, t-ratio, and p-value. Bias diagnostics are provided to judge model tendency to over or underestimate calculated loads. Percent bias (PBIAS) measures the average tendency of the simulated data to be larger or smaller than observed data (Moriasi, ibid.). USGS documentation recommends that models with percent bias exceeding ± 25% not be used. The Nash Sutcliffe Efficiency (NSE) index is a normalized statistic that determines relative magnitude of the residual variance ("noise") compared to the measured data variance ("information"). It ranges from $-\infty$ to 1.0 with values > 0.5 generally considered acceptable (Moriasi, ibid.). Following calibration, the estimation process uses the resulting regression to estimate loads over the time period of interest. Mean load estimates, standard errors, and confidence intervals are reported as time series, monthly averages, and seasonal averages (Runkel et al., ibid.).

The regression approach to load estimation used by the LOADEST program is not well suited for small, urban watersheds like Sessom Creek due to their flashy discharge response, rapidly changing water quality, and hysteresis of entrained constituents during runoff events. A typical application of LOADEST uses a 1-day time step interval and estimates loads spanning multiple years. Regression methods perform better when applied to large watersheds with slow runoff response times which dampens rapid changes in flow, water quality, hysteresis, etc. This reduces variation in the relationship between discharge and constituent concentration and produces better statistical estimates of long-term loading.

In order to minimize Sessom Creek scale and temporal response issues as much as possible while still preserving individual storm characteristics, observed discharge and water quality values were resampled from their original intensive short non-uniform intervals between 3 and 30 minutes to fixed 1-hour frequency intervals. See data preparation section for details regarding up and down sampling procedures. Hourly average discharge data were used for the LOADEST's estimation file which accepts a maximum number of 24 daily observations. Calibration records lacking either a discharge value or measured concentration value were discarded. The hourly mean discharge values were paired with concurrent mean hourly concentration values, plotted, and examined visually for anomalies. Suspended sediment and total phosphorus showed clear relationships to discharge while total nitrogen showed little to none (Figure 4Figure 5Figure 6). Based on this, only suspended sediment and total phosphorus data were formatted specific to LOADEST requirements (i.e., units and numeric formats) and exported as .csv format files for further processing.

The LOADEST estimation file contained a record of hourly mean discharge. This record was used to estimate daily, monthly, and annual load for 2018 and part of 2019 based on the regression equation developed in the calibration process. The same estimation file was used for both suspended sediment and total phosphorus loads. The LOADEST program header and control files defined the remaining required input parameters which included: model selection, number of constituents, reporting units, and desired outputs.

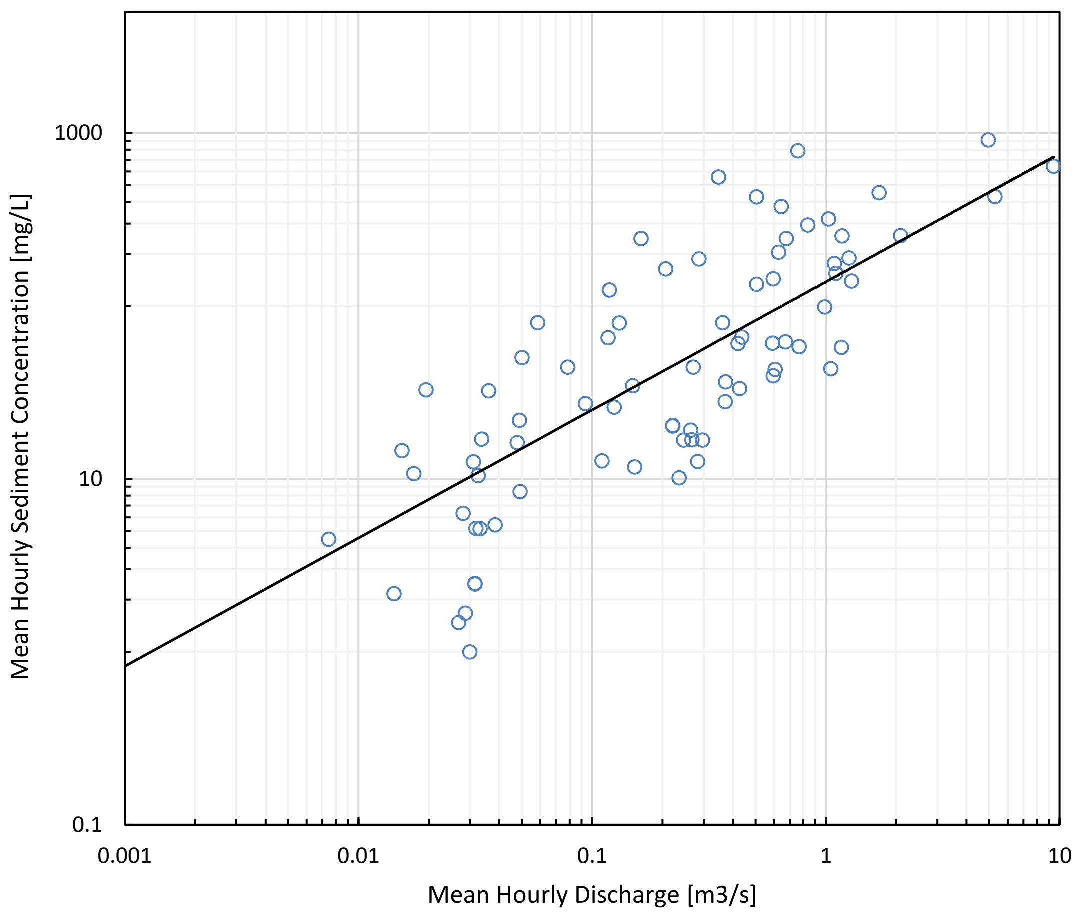

Figure 4. Relationship between mean hourly discharge and mean hourly sediment concentration at Sessom Creek, 27 March to 7 December 2018.

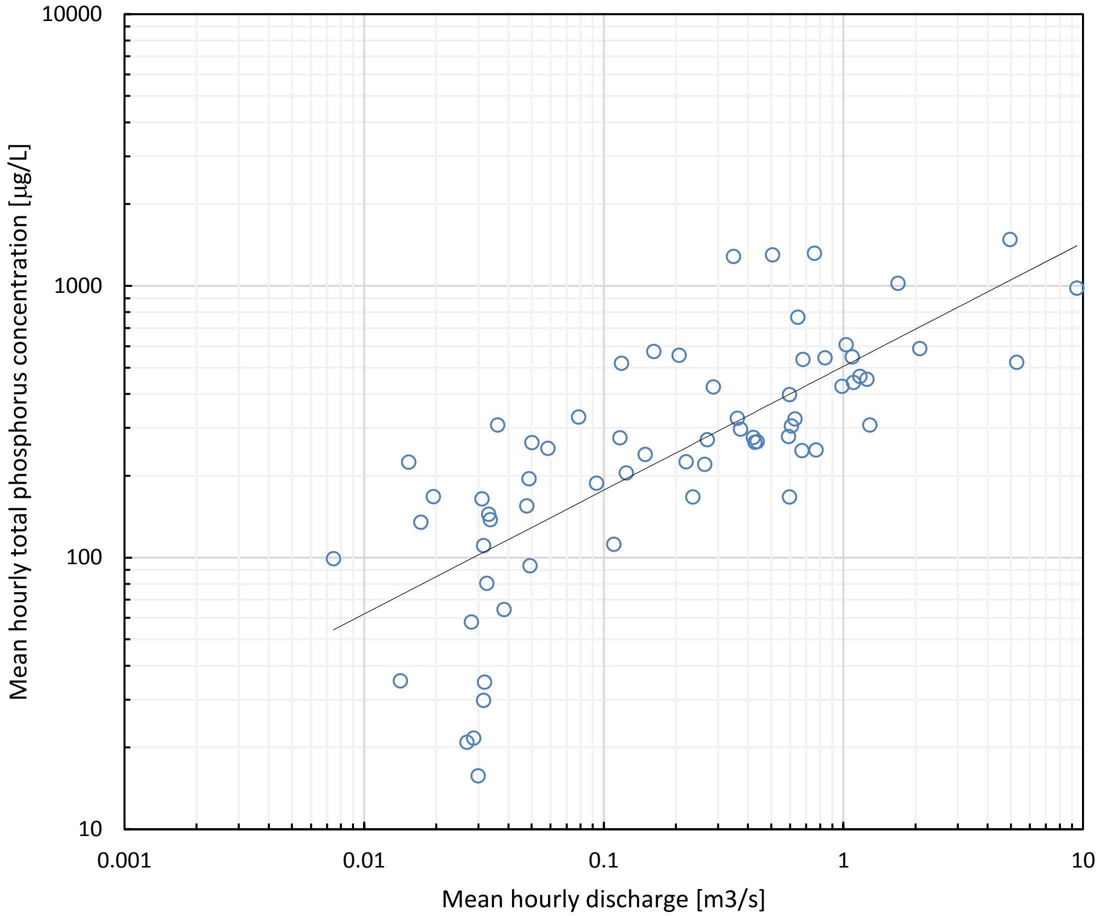

Figure 5. Relationship between mean hourly discharge and mean hourly total phosphorus concentration at Sessom Creek, 27 March to 7 September 2018.

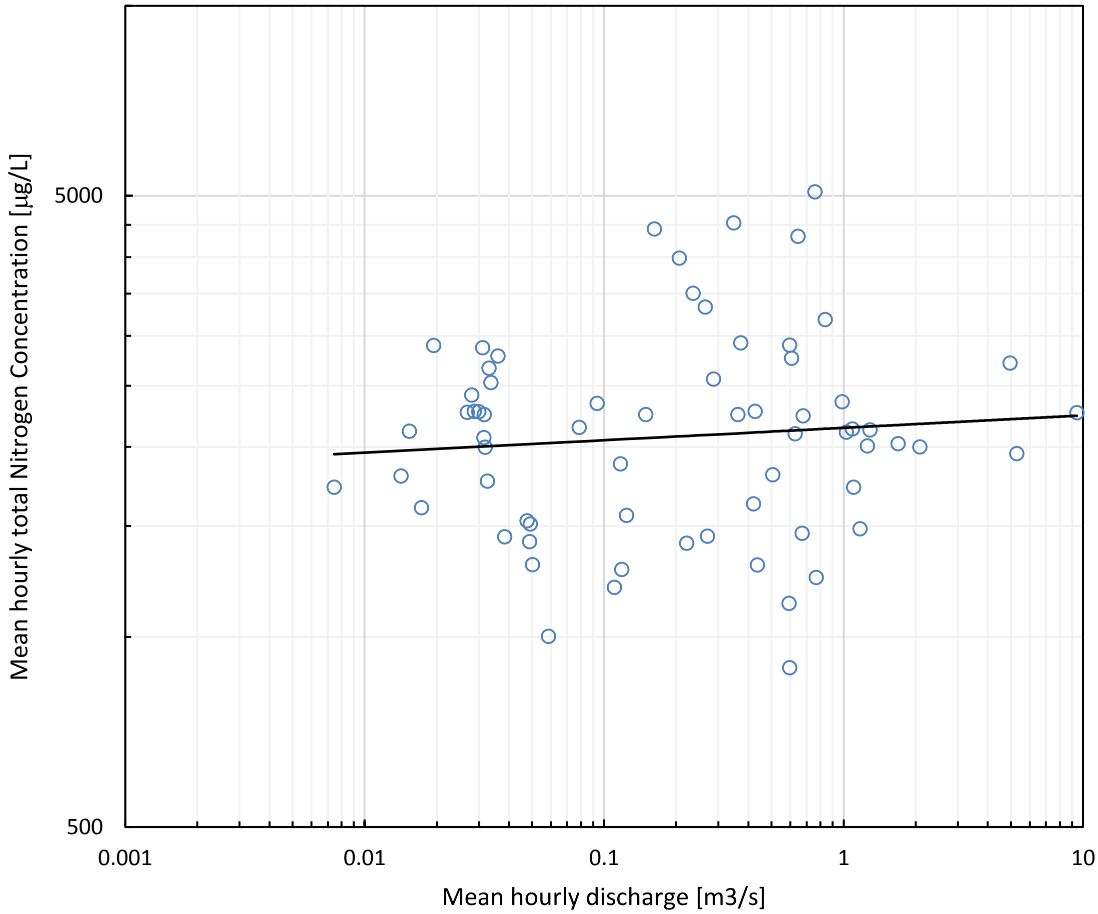

Figure 6. Relationship between mean hourly discharge and mean hourly total nitrogen concentration at Sessom Creek, 27 March to 7 September 2018.

Load estimation based on continuous turbidity

Traditionally, suspended sediment loads have been computed from results of physical sample collection and analysis of stream flow data. The computation technique relies upon the availability of frequent stream flow time-series data and a concurrent estimation of suspended sediment concentration, interpolated from measured samples. As a result, periods with infrequent observations must be interpolated. These unobserved periods can include a substantial cumulative fraction of the sediment load which greatly affects the uncertainty associated with the estimate.

Turbidity is an expression of the optical properties of a sample that caused light rays to be scattered and absorbed rather than transmitted in a straight line through a sample. Turbid water is heavily influenced by the presence of suspended mineral clay, silt, organic matter, and other fine particles. When proportional, a turbidity-suspended sediment relationship can be established through linear regression analysis. The turbidity-suspended sediment regression model, in turn, can be used to compute suspended sediment values from turbidity data within the turbidity meter's measurement range. Continuously monitored turbidity data enable computation of a suspended sediment concentration time series that can be paired with a streamflow time series to compute continuous sediment load without need for interpolation or estimation (Rasmussen et al., 2009).

A plot of turbidity versus suspended sediment concentration measured as total suspended solids showed a clear relationship (Figure 7). Suspended sediment concentration was estimated as a function of turbidity by constructing a statistical regression between paired observations of turbidity and sediment concentration. Estimations of suspended sediment loads exported from Sessom Creek Watershed based on continuous turbidity measurements were computed for the 14-month monitoring period using the USGS Turbidity Spreadsheet tool to model and estimate loads.

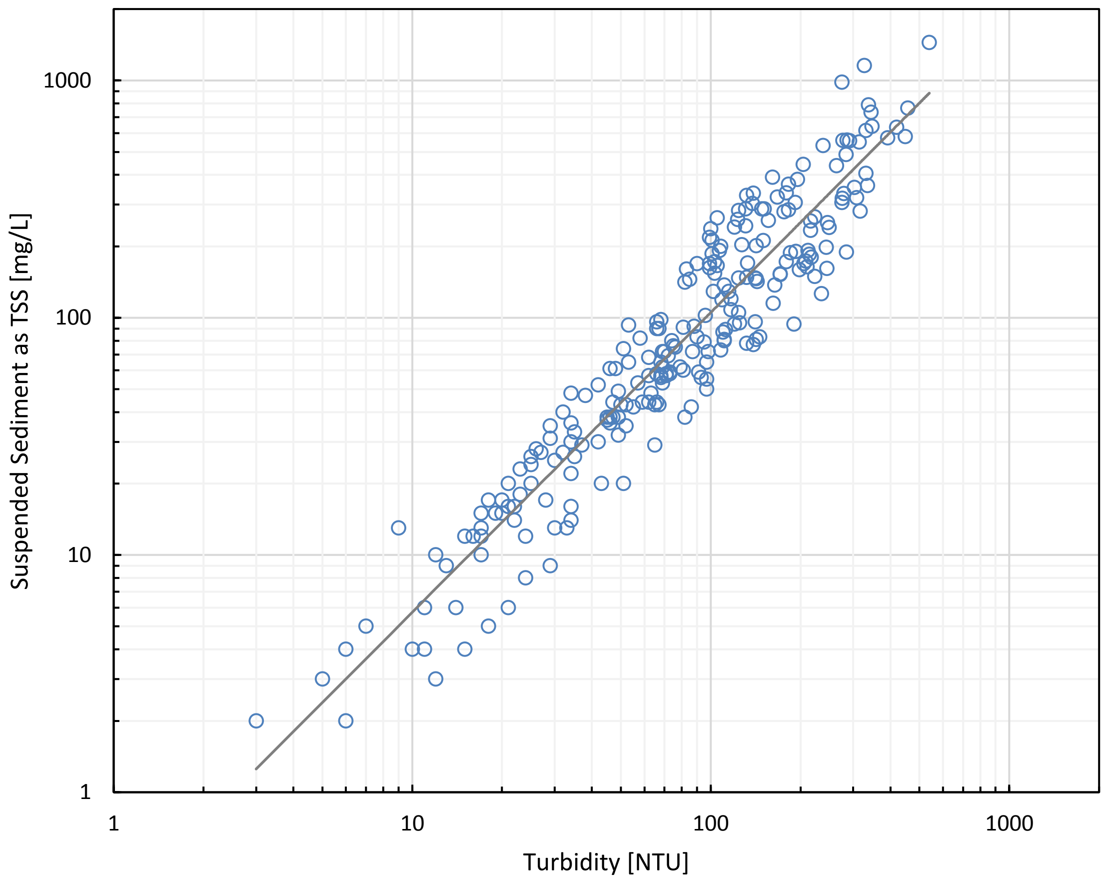

Figure 7. Relationship between turbidity (15-min interval) and suspended sediment measured as total suspended solids (TSS) at Sessom Creek, 27 March to 7 December 2018.

Spatial assessment of water and sediment budgets using SWAT

Continuous time-step watershed models are useful to complement monitoring data in a watershed to estimate water budgets and to identify critical source areas of soil erosion and other constituent pollutants. The Soil and Water Analysis Tool (SWAT) is a watershed-scale eco-hydrological model developed for evaluating land management effects on watershed hydrology and pollutant transport on landscape and through river networks. In this study, SWAT was used to evaluate soil erosion processes in the highly urbanized Sessom Creek Watershed (SCW). The SCW contributes a disproportionately large amount of sediment during storm runoff events which negatively affects aquatic ecosystem health and river recreation. It was hypothesized that the high ratio of impervious cover in the Sessom drainage area makes stormwater runoff events "flashy". This is characterized by pronounced high peak flow rates of short duration in runoff hydrographs. This situation generates landscape and aquatic soil erosion processes with greater erosive sheer velocity than in non-urban watersheds. The short length of concentrated flow paths in Sessom Creek, flashy stormwater flowing off impervious cover, lack of stormwater management infrastructure, and steep land slopes combine to create rainfall-stream discharge (at the watershed outlet) events shorter than 24 hours, and often only 2-4 hours. Under these conditions, daily time-step models tend to miss sub-daily rainfall-runoff events. As a result, the model may be over-parameterized during model calibration processes to compensate for such gaps in representing dynamic hydrographic processes. Sub-daily simulations can more accurately represent short-duration storm events and provide better estimates of sediment sources. This study aimed evaluate time-scale effects on streamflow and sediment yield prediction using the SWAT model. Specifically, the Sessom SWAT model was optimized at both 15-minute and daily intervals against measured streamflow and sediment yield at the watershed outlet. Monitoring data were applied at both 15-minute and daily intervals to compare goodness-of-fit between simulated and observed flow and sediment yield. Critical source areas (CSA) were identified in the watershed to provide watershed managers with data that can be used to support targeted erosion control and stormwater management efforts. The effect of a proposed detention pond on sediment yield reduction was also evaluated as a stormwater management scenario.

SWAT landuse description

Sessom Creek is a headwater tributary of the San Marcos River, draining 1.73 km^2 of urban lands on a hilly landscape in Hays County, Texas (Figure 8). Major landuses are urban (87%) and forest (12%). The watershed is on a hilly landscape with more than 59% of lands are on steep slopes greater than 6 % (Figure 9). Soils are predominantly clayey loam which is characterized by high runoff potential due to poor drainages. Climate in San Marcos, TX is semi-arid, with mean annual precipitation of 838 mm/yr (2007 to 2017). May, September, and October are on average the wettest months, while February and August are the driest (National Oceanic and Atmospheric Administration, NOAA, 2017). The maximum mean temperature is 37°C during the hottest months (July and August), and coldest months are December and January (NOAA, 2017).

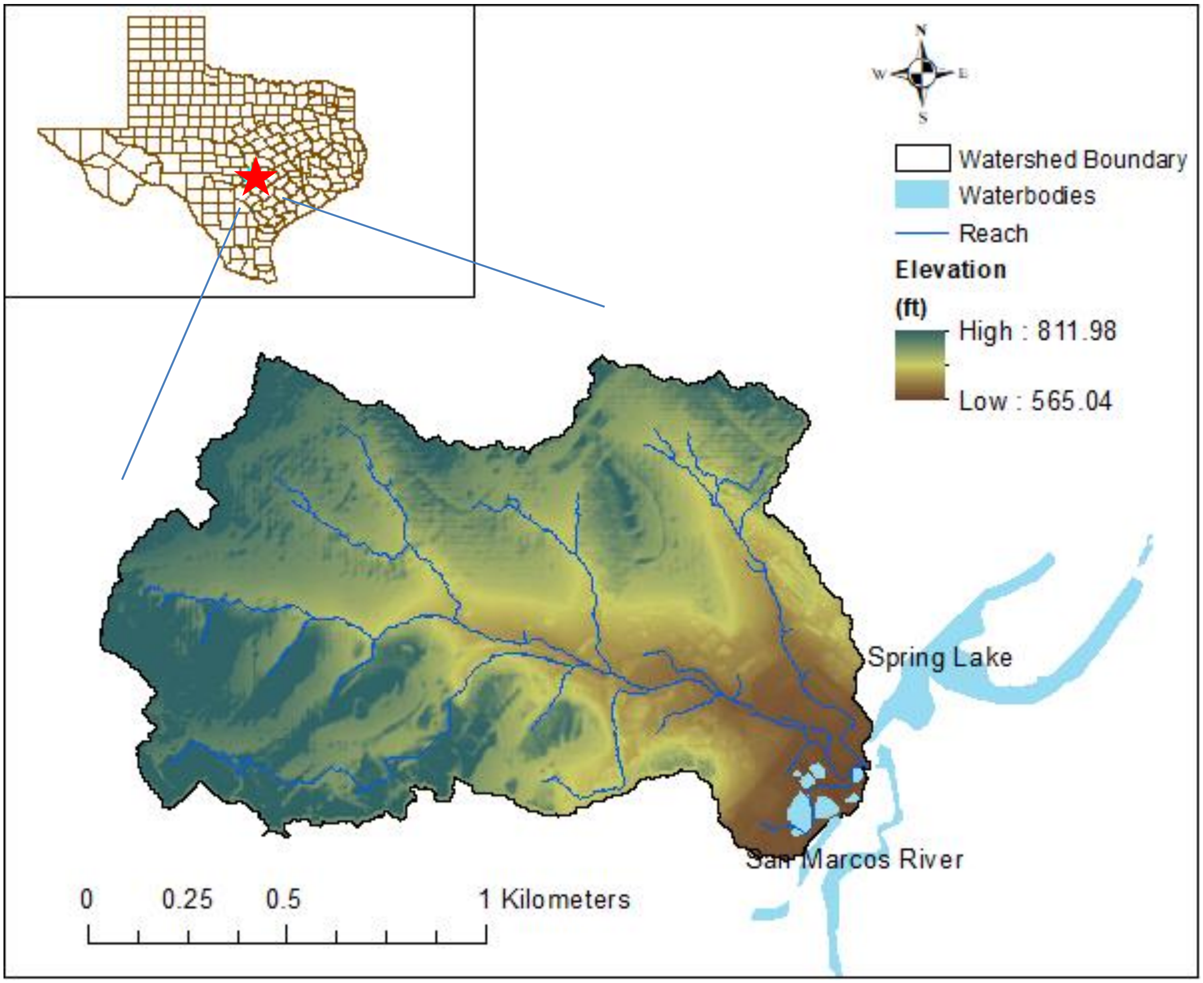

Figure 8. The Sessom Creek watershed.

SWAT input data

A 3-meter elevation map was used to delineate the stream network in the 173-hectare watershed. Soils were characterized using US Soil Survey Geographic Database (SSURGO) information. An enhanced landuse map based on a field survey and the United States Geological Survey (USGS) National Land Cover Dataset (NLCD) published in 2016 was used to provide landuse information. Land slope is defined in five classes (0-3%, 3-6%, 6-15%, 15-25%, 25-68%). These spatial data layers were used to delineate the watershed into 82 sub-basins and 1,547 hydrologic response units (HRUs). In the SWAT Sessom model, each HRU represents approximately 0.11 ha of land. Precipitation data used in Sessom Creek analysis was obtained from two sources, the National Oceanographic and Atmospheric Administration (NOAA) service and the Weather Underground, an on-line commercial weather service providing private citizen-collected real-time weather information. Fifteen-minute and 1-hour precipitation time series data were used to drive the model. See data preparation section for details on time series preparation.

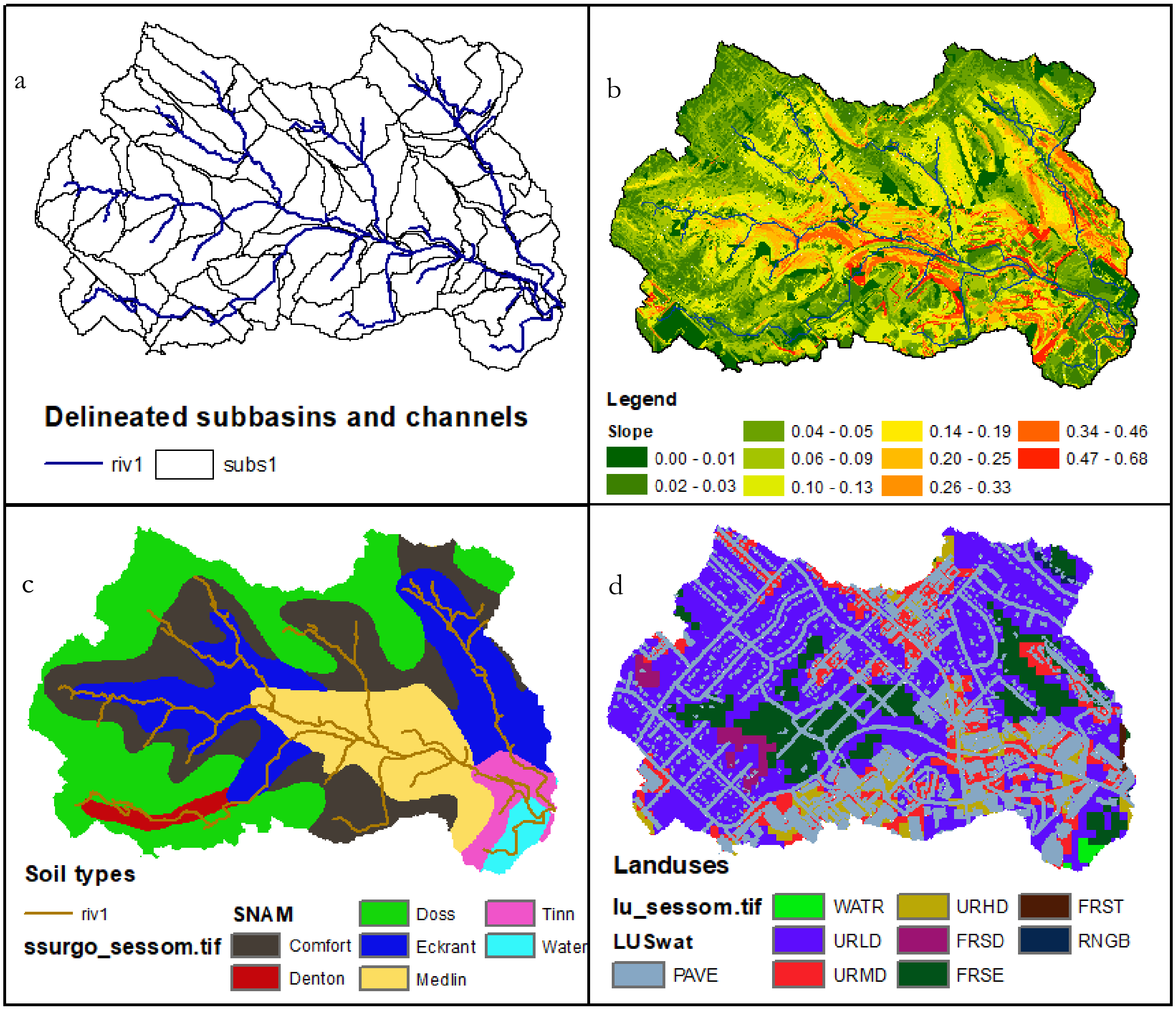

Figure 9. SWAT input data layers. a: main channels and sub-basins, b: land slope, c: soil names, d: land use types.

SWAT modeling processes

Two SWAT input datasets were prepared, one for daily time-step simulation and another for sub-daily simulation. In daily simulation, stormwater runoff was estimated by the NRCS-CN method, while the Green & Ampt method modified by Mein-Larson was used to estimate stormwater runoff at 15-minute intervals in the sub-daily simulation. An enhanced Variable Storage Coefficient method was used for dynamic channel flow routing. The Modified Universal Soil Loss Equation (MUSLE) was used to estimate landscape soil erosion in the daily model. In the 15-min model, splash erosion by raindrops, overland flow erosion and channel bed erosion were estimated based on Jeong et al. (2011). Flow and sediment yield were examined as response variables and calibrated against observed data collected near the watershed outlet in 2018.

SWAT Sessom models, daily and 15-min intervals, were prepared to run 8 years (2010-2017) for model warm up and 12 storm events in 2018 for evaluation. Due to the short one-year monitoring period, the model was calibrated for the first 8 months on streamflow and sediment yield and then validated for the remaining 4 months in 2018. Model parameters including CN2, KSAT, AWC, and UALPHA were evaluated for parameterization during the calibration process.

The San Marcos Water Quality Protection Plan (WQPP, JGLLC, 2015) recommended focusing on controlling sediment sources in the Sessom Creek watershed as a means to minimize water quality impacts to San Marcos River. As a part of stream restoration recommendations, Hartigan et al. (2017) recommended that a pond system could capture sediment from the Windmill sub-catchment while also providing significant control of erosive flows that are impacting Sessom Creek. The recommended 25,000 ft^3 capacity detention pond is evaluated as a best management practice (BMP) scenario using the calibrated 15-min model. For simulation, a detention pond was placed in the Windmill creek tributary near the confluence of the creek and Sessom Creek. A detention pond with a stepwise weir system which attenuates peak flows in the Windmill tributary by 70% was assumed.

RESULTS

Observed precipitation, discharge, turbidity, and water quality

The Sessom Creek continuous discharge record showed a total of 42 runoff events exceeding the sampling threshold discharge rate of 0.1 m^3/s during the monitored period from 1 January 2018 to 28 February 2019. Fourteen of these events were sampled, and 24 samples per event were analyzed for water quality parameters. Cumulative rainfalls for these events ranged from 9 to 129 mm (Figure 10). Two dates, 28 March and 7 December had two storms on the same day producing runoff events separated by several hours. All events were analyzed for suspended sediment and nutrients except two events occurring on 7 December which were analyzed for suspended sediment only, which also allowed assessment of the TSS-SSC relationship. A flow duration curve clearly shows the ephemeral nature of Sessom Creek discharge. Discharges exceeding 0.001 m^3/s occur 64% of the time, while discharge above the sampling threshold (0.1 m^3/s), resulting from storm runoff, occur less than 2.5% of the time (Figure 11). Direct computation of constituent loads and exports for each monitored event was accomplished by multiplying each measurement interval's constituent concentration by the interval's flow volume and summing the products over the event. Sampled storm summary statistics are presented in Table 1. Sampled storm summary statistics:

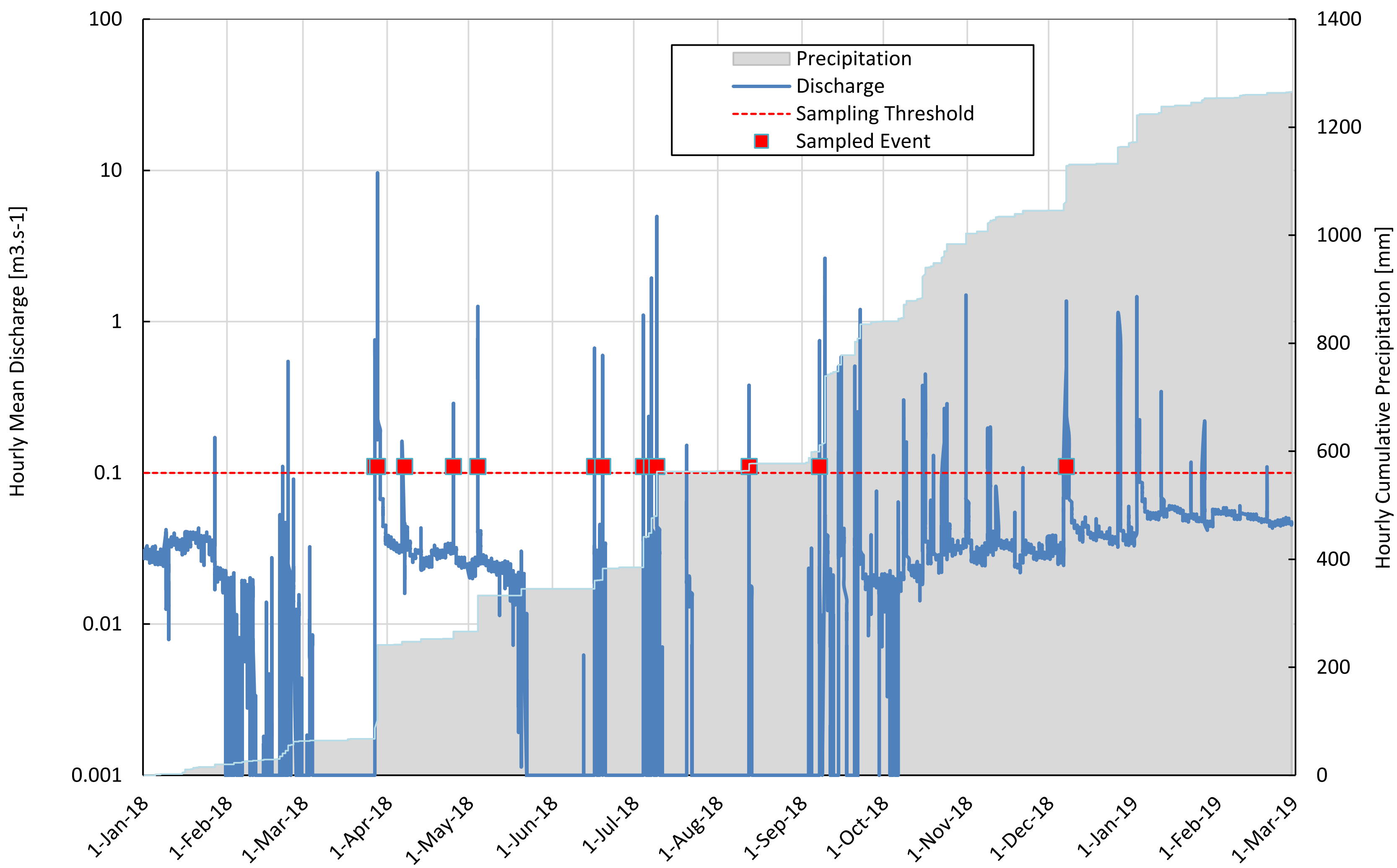

Figure 10. Sessom Creek average hourly discharge, sampling threshold, sampled events, and cumulative precipitation. Monitoring period from 1 January 2018 to 28 February 2019. Two days (28 March and 7 December) had two separate sampled events on the same day.

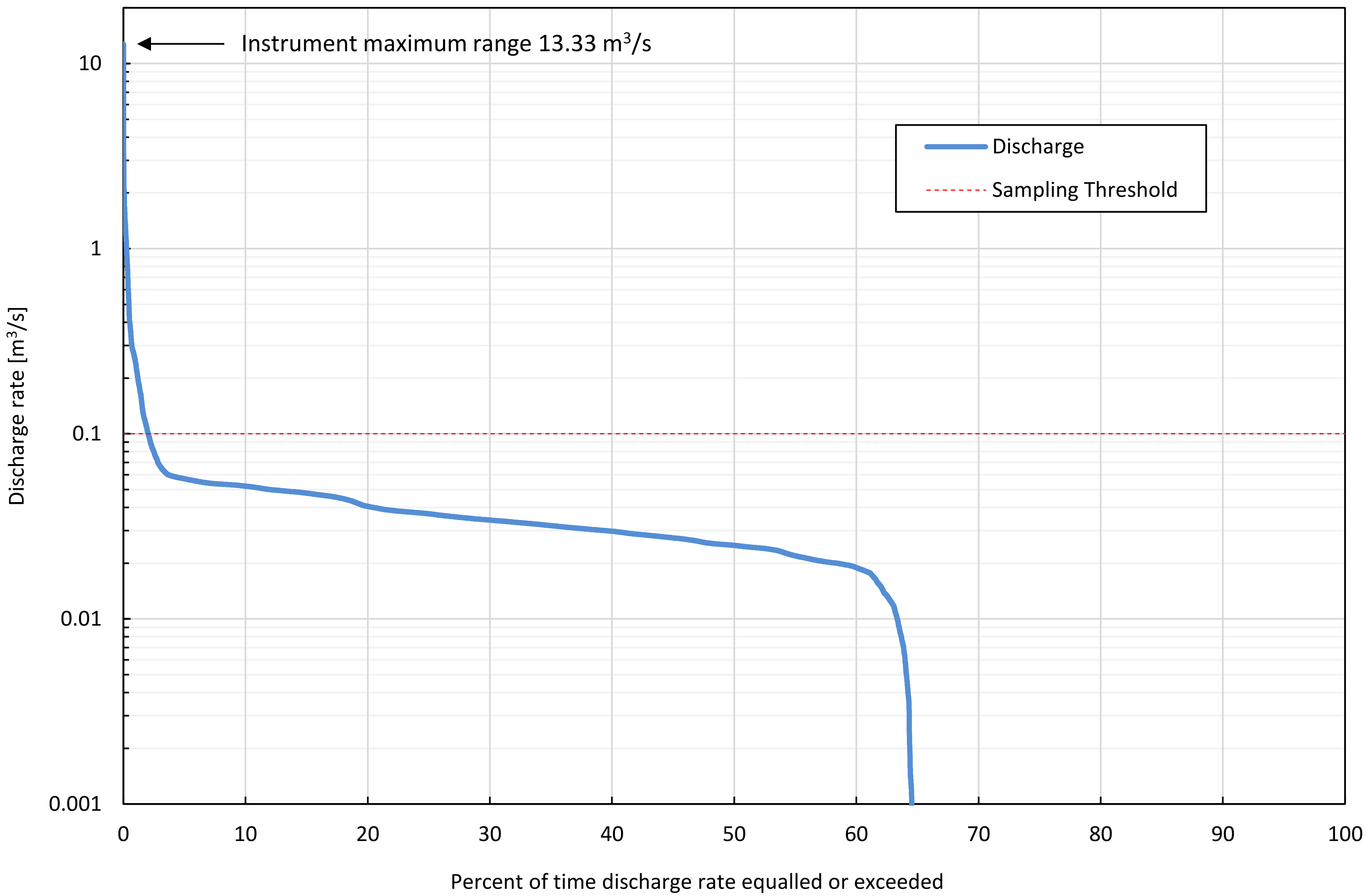

Figure 11. Sessom Creek flow duration curve.
Curve based on continuous NOAA record between 1 January 2018 and 28 February 2019. Maximum discharge measurement 13.33 m^3/s (instrument limitation) and minimum was 0.001 m^3/s. Dotted red line indicates automated sampler activation threshold (0.1 m^3/s) above which water quality samples were collected.

Table 1. Sampled storm summary statistics:
Sediment, total phosphorus, and total nitrogen were determined from automated sampling when discharge exceeded 0.01 m3/s. Sample collection used an increasing, non-uniform time interval scheme (6 samples @ 3-min, 6 samples @ 5-min, 6 samples @ 15-min, and 6 samples @ 30-min). Reported variables for each event include cumulative rainfall, sampling duration, mean discharge, peak discharge, volume of discharge, mean suspended sediment concentration, mean total phosphorus concentration, mean total nitrogen concentration, suspended sediment export, total phosphorus export, and total nitrogen export.

Event ID	Event Date [2018]	Event Cumulative Rainfall	Event Sampling Duration	Event Mean Discharge	Event Peak Discharge	Event Volume Discharge	Mean Suspended Sediment	Mean Total Nitrogen	Mean Total Phosphorus	Suspended Sediment Export	Total Nitrogen Export	Total Phosphorus Export
[#]	[day-mon]	[mm]	[min]	[m3/s]	[m3/s]	[m3]	[mg/L]	[µg/L]	[µg/L]	[kg]	[kg]	[kg]
1*	27,28-Mar	129	364	2.979	13.329	63389	520	2320	782	32945	147.1	49.6
2	28-Mar	33	258	0.933	3.268	13646	171	2329	465	2334	31.8	6.3
3	7-Apr	9	285	0.050	0.536	818	130	3421	322	107	2.8	0.3
4	25-Apr	13	285	0.127	0.447	2008	143	2690	382	288	5.4	0.8
5	4-May	67	285	0.835	2.185	12867	145	1944	375	1871	25	4.8
6	16-Jun	15	285	0.158	1.461	2554	334	3889	745	854	9.9	1.9
7	19-Jun	21	285	0.250	1.150	3510	45	1101	195	157	3.9	0.7
8	4-Jul	57	285	0.657	2.605	9813	183	1767	452	1795	17.3	4.4
9	7-Jul	28	285	0.502	3.365	7499	413	1923	1016	3099	14.4	7.6
10	9-Jul	82	285	1.607	9.022	21417	664	2559	1095	14212	54.8	23
11	12-Aug	12	285	0.082	1.201	1209	442	4055	1070	535	4.9	1.3
12	7-Sep	12	285	0.152	1.443	2349	223	2190	498	524	5.1	1.2
13**	7-Dec	28	285	0.271	1.079	4424	59	na	na	259	na	na
14**	7-Dec	52	285	0.643	1.532	9471	40	na	na	374	na	na
Mean			289	0.482	2.253	7045	251	616	2516	4239	27	9
S.D.			23	0.450	2.235	6175	193	313	881	9026	41	14

* Actual discharges and exports unknown due to flow meter limitation. Two extra samples collected for this event.
** No nutrient analysis for these events.

Hysteresis patterns

Fifteen-minute interval discharge and turbidity time series data were used to examine suspended sediment hysteresis responses to the 42 storms observed in Sessom Creek Watershed over the 14-month monitoring period (Table 2). A total of 80 peaks were characterized resulting in 28 clockwise loops, 5 clockwise figure-8 loops, 31 counterclockwise loops, 10 counterclockwise figure-8 loops, and 5 straight lines (i.e., no loop or hysteresis). Twenty-four events had one peak, 6 events had 2 peaks, 2 events had 3 peaks, 4 events had 4 peaks, 2 events had 5 peaks, and one event had 6 peaks. Summaries for all events, events with a single peak, and events with multiple peaks are shown in Table 3.

Table 2. Sessom Creek turbidity hysteresis data.
Includes: storm date, event number, number of peaks, duration, sum of standardized rising limb values (ST_{RL}), sum of standardized falling limb values (ST_{FL}), hysteresis index, loop direction, and hysteresis loop type for 42 storm runoff events occurring between 1 January 2018 and 28 February 2019.

Date	Event	Peak	Duration	ST_{RL}	ST_{FL}	Index	Loop Direction	Loop Type
1/27/2018	1	1	45	0.63	0.89	-0.26	Counter	3
2/21/2018	2	1	15	0.50	0.00	0.50	Clockwise	1
2/23/2018	3	1	45	0.64	0.10	0.54	Clockwise	1
2/23/2018	3	2	105	0.57	0.79	-0.21	F8-Counter	4
2/25/2018	4	1	30	0.50	0.54	-0.04	Counter	3
3/27/2018	5	1	60	0.66	0.53	0.13	Clockwise	1
3/28/2018	6	1	60	0.76	0.55	0.19	Clockwise	1
3/28/2018	6	2	165	0.64	0.31	-0.28	Counter	3
3/28/2018	6	3	345	0.66	0.70	-0.04	F8-Counter	4
3/28/2018	6	4	345	0.77	0.68	0.09	F8-Clockwise	2
3/28/2018	6	5	180	0.56	0.24	0.32	Clockwise	1
4/7/2018	7	1	30	0.37	0.53	-0.16	Counter	3
4/25/2018	8	1	75	0.61	0.54	0.07	F8-Clockwise	2
4/25/2018	8	2	75	0.69	0.58	0.11	F8-Clockwise	2
5/4/2018	9	1	135	0.52	0.62	-0.12	Counter	3
5/4/2018	9	2	300	0.81	0.61	0.20	Clockwise	1
6/16/2018	10	1	45	0.55	0.40	0.16	Clockwise	1
6/18/2018	11	1	30	0.51	0.50	0.01	Clockwise	1
6/19/2018	12	1	45	0.62	0.25	0.09	Clockwise	1
6/19/2018	12	2	60	0.74	0.51	0.11	Clockwise	1
6/19/2018	12	3	60	0.06	0.52	-0.58	Counter	3
7/4/2018	13	1	240	0.48	0.68	-0.21	Counter	1
7/6/2018	14	1	60	0.87	0.83	0.00	Straight	5
7/7/2018	15	1	150	0.19	0.77	-0.58	Counter	3
7/9/2018	16	1	60	0.63	0.15	0.20	Clockwise	1
7/9/2018	16	2	270	0.36	0.67	-0.31	Counter	3
7/20/2018	17	1	75	0.80	0.48	0.26	Clockwise	1
7/20/2018	17	2	45	0.11	0.37	-0.47	Counter	3
8/12/2018	18	1	75	0.45	0.85	-0.40	Counter	3
9/7/2018	19	1	60	0.63	0.46	0.17	Clockwise	1
9/14/2018	20	1	60	0.50	0.55	-0.05	Counter	3
9/14/2018	20	2	45	0.56	0.75	-0.24	Counter	3
9/15/2018	21	1	105	0.80	0.67	0.04	Clockwise	1
9/15/2018	21	2	90	0.73	0.81	-0.09	Counter	3
9/15/2018	21	3	105	0.62	0.71	-0.11	F8-Counter	4
9/20/2018	22	1	90	0.84	0.67	0.17	Clockwise	1
9/21/2018	23	1	45	0.30	0.67	-0.37	Counter	3

9/22/2018	23	1	270	0.31	0.67	-0.36	Counter	3
9/28/2018	24	1	45	0.48	0.50	-0.02	Straight	5
10/6/2018	25	1	15	0.50	0.50	0.00	Straight	5
10/8/2018	26	1	240	0.81	0.84	-0.03	Counter	3
10/9/2018	27	1	45	0.50	0.58	-0.20	Counter	3
10/15/2018	28	1	180	0.51	0.62	-0.15	F8-Counter	4
10/15/2018	28	2	60	0.55	0.56	-0.02	F8-Counter	4
10/15/2018	28	3	75	0.63	0.92	-0.32	Counter	3
10/15/2018	28	4	75	0.51	0.63	-0.17	Counter	3
10/16/2018	29	1	75	0.91	0.80	0.11	Clockwise	1
10/16/2018	29	2	60	0.67	0.86	-0.19	Counter	3
10/16/2018	29	3	135	0.53	0.75	-0.22	Counter	3
10/16/2018	29	4	45	0.45	0.77	-0.38	Counter	3
10/16/2018	29	5	90	0.56	0.42	0.12	Clockwise	1
10/19/2018	30	1	75	0.35	0.72	-0.40	Counter	3
10/23/2018	31	1	60	0.90	0.25	0.10	Clockwise	1
10/23/2018	31	2	75	0.73	0.55	0.17	Clockwise	1
10/23/2018	31	3	60	0.87	0.87	-0.04	Straight	5
10/23/2018	31	4	180	0.44	0.45	-0.03	F8-Counter	4
10/24/2018	32	1	45	0.42	0.75	-0.37	F8-Counter	4
10/24/2018	32	2	90	0.53	0.73	-0.22	F8-Counter	4
10/24/2018	32	3	75	0.78	0.76	-0.11	Counter	3
10/24/2018	32	4	120	0.54	0.40	0.10	F8-Clockwise	2
10/31/2018	33	1	180	0.58	0.91	-0.33	Counter	3
11/9/2018	34	1	60	0.41	0.51	-0.12	Counter	3
11/9/2018	34	2	105	0.47	0.40	0.07	Clockwise	1
11/21/2018	35	1	45	0.50	0.39	0.10	Clockwise	1
12/7/2018	36	1	195	0.85	0.48	0.37	Clockwise	1
12/7/2018	36	2	270	0.51	0.73	-0.22	Counter	3
12/7/2018	36	3	120	0.71	0.42	0.19	Clockwise	1
12/7/2018	36	4	165	0.74	0.29	0.27	Clockwise	1
12/7/2018	36	5	255	0.71	0.60	0.11	F8-Clockwise	2
12/7/2018	36	6	150	0.72	0.60	-0.07	F8-Counter	4
12/8/2018	37	1	570	0.52	0.44	0.09	Clockwise	1
12/27/2018	38	1	195	0.47	0.79	-0.32	Counter	3
1/2/2019	39	1	75	0.54	0.21	0.30	Clockwise	1
1/2/2019	39	2	195	0.76	0.83	-0.07	Counter	3
1/2/2019	39	3	345	0.53	0.44	-0.03	Counter	3
1/2/2019	39	4	300	0.41	0.53	-0.14	Counter	3
1/3/2019	40	1	375	0.56	0.51	-0.01	Straight	5
1/22/2019	41	1	120	0.50	0.38	0.13	Clockwise	1
1/27/2019	42	1	105	0.75	0.41	0.34	Clockwise	1
1/27/2019	42	2	105	0.63	0.65	-0.04	F8-Counter	4

Table 3. Turbidity hysteresis summary.
Includes: n, % of total, mean hysteresis index (HI), and hysteresis standard deviation for all storm events, single peak events, and multi-peak events.

Hysteresis	All Events				Single Peak Events				Multi Peak Events			
	n	% Total	Mean HI	S.D. HI	n	% Total	Mean HI	S.D. HI	n	% Total	Mean HI	S.D HI
Type 1	28	0.35	0.19	0.13	9	0.36	0.16	0.14	19	0.35	0.21	0.13
Type 2	5	0.06	0.10	0.02	0	0.00	-	-	5	0.09	0.10	0.02
Type 3	32	0.40	-0.24	0.15	12	0.48	-0.29	0.16	20	0.36	-0.21	0.14
Type 4	10	0.13	-0.13	0.11	0	0.00	-	-	10	0.18	-0.14	0.11
Type 5	5	0.06	-0.01	0.02	4	0.16	-0.01	0.01	1	0.02	-0.04	-
Total	80				25				55			

Sediment and nutrient loads estimated by discharge

Initial data exploration was performed by visually examining plots of suspended sediment concentration and total phosphorus concentration versus stream discharge. Multiple LOADEST runs of different data arrangements (i.e., all records, partial records, etc.), sub-divisions (i.e., rising and falling limbs of the hydrograph), time variables (i.e., seasonal, monthly, trend, etc.), and transformations (i.e., log, log-log, etc.) were required to produce acceptable regressions to estimate Sessom Creek sediment and total phosphorus loads from continuous discharge measurements.

A log-log plot of measured suspended sediment concentration vs discharge during the 14 runoff events indicated a linear relationship (Figure 4). Concurrent discharge – suspended sediment records with sediment concentration values near the method detection limit (i.e., ± 2 mg/L), discharge values less than the 0.1 m^3/s sampling threshold, and discharge values greater than the 13.33 m^3/s instrument maximum were excluded from the calibration data set and the final regression was built on the remaining 73 records (APPENDIX 1 - LOADEST).

Nutrient concentrations in runoff were measured during 12 runoff events. Log-log plots examining nutrient concentration (i.e., nitrogen and phosphorous forms) versus discharge indicated that nitrogen in any form, and dissolved phosphorous, had little to no relationship with discharge while total phosphorous showed a linear relationship similar to that of suspended sediment (Figure 5Figure 6). Total nitrogen was given no further consideration in the LOADEST model. As with sediment, concurrent total phosphorus concentration - discharge records with discharge values less than the 0.1 m^3/s sampling threshold, and discharge values greater than the 13.33 m^3/s instrument maximum were excluded from the calibration data set and the final regression for total phosphorus was based on the remaining 38 records (APPENDIX 1 - LOADEST).

Initially, LOADEST software's automated procedures were used to select the best fit model based on the calculated AIC value. Results however were judged to unfairly overfit both sediment and total phosphorus data due to an included trend term. As the data were collected over one year, Model 4 was manually selected from available models in order to include terms for the constituent concentration dependence on discharge (*a* and *b*) and seasonal variation (*c* and *d*). The model form, best fit coefficients, regression statistics, and bias diagnostics are shown in Table 4. Because the data set contained no censored values, AMLE/MLE coefficients were used to estimate loads. Complete LOADEST outputs for both suspended sediment and total phosphorus are presented in APPENDIX 2 - LOADEST outputs

The final LOADEST suspended sediment concentration regression model showed a reasonably good fit with an adjusted R^2 value of 0.66. Residual plots showed the model assumptions of normality and heteroscedasticity were met (see APPENDIX 3 - LOADEST). Concentration PBIAS was low at 3% and Nash Sutcliff ratio between observed and estimated loads was acceptable at 0.57. More points lying above the 1:1 line on a plot of observed vs estimated loads (Figure 12) suggests a positive bias (i.e., the model may tend to overestimate sediment loads). The load estimates generated by LOADEST showed good agreement with measured sediment loads over the 14-month monitoring period (Figure 13). A rating curve for predicting the suspended sediment load from discharge measurements is given Figure 14.

The final LOADEST total phosphorus concentration regression model showed a fair fit with an adjusted R^2 value of 0.52. Residual plots showed the model assumptions of normality and heteroscedasticity were met (see APPENDIX 3 - LOADEST). Concentration PBIAS was very low at -0.59% and Nash Sutcliff ratio between observed and estimated loads was acceptable at 0.62. As with suspended sediment, slightly more points lying above the 1:1 line on a plot of observed vs estimated loads (Figure 15) suggests positive bias (i.e., the model may tend to overestimate total phosphorus loads). The load estimates generated by LOADEST showed good agreement with measured total phosphorus loads over the 14-month monitoring period (Figure 16). A rating curve for predicting the total phosphorus load from discharge measurements is given in Figure 17.

Table 4. Regression coefficients, statistics, and bias diagnostics for concentration models used to estimate suspended sediment and total phosphorus loads for Sessom Creek.

Constituent	AMLE Coefficients				Regression statistics			Bias diagnostics	
	a	b	c	d	n	Adjusted R^2	Residual Variance	PBIAS	NSE
Suspended Sediment	3.49 (0.12)	0.73 (0.07)	*-0.20* (0.16)	0.55 (0.16)	73	0.66	0.72	3.08	0.57
Total Phosphorus	6.10 (0.22)	0.36 (0.06)	0.19 (0.10)	*-0.10* (0.30)	38	0.52	0.15	-0.59	0.62

Notes: the regression form for selected Model 4 is $\ln(Conc) = a + b(\ln Q) + c\sin(2\pi T_d) + d\cos(2\pi T_d)$: where *Conc* is the constituent concentration, in milligrams (sediment) or micrograms (total phosphorus) per liter; ln*Q* is the natural log of stream discharge minus the center of the natural log of stream discharge, in cubic feet per second (center of natural log of discharge for sediment = 1.71, phosphorus = 3.32); T_d is decimal time of the calibration period minus the center of decimal time of the calibration period (center of decimal time for sediment = 2018.581, phosphorus = 2018.397); and *a*, *b*, *c*, and *d* are AMLE regression coefficients with standard deviations in parentheses. All coefficients are significant at the $p < 0.05$ level except those italicized.

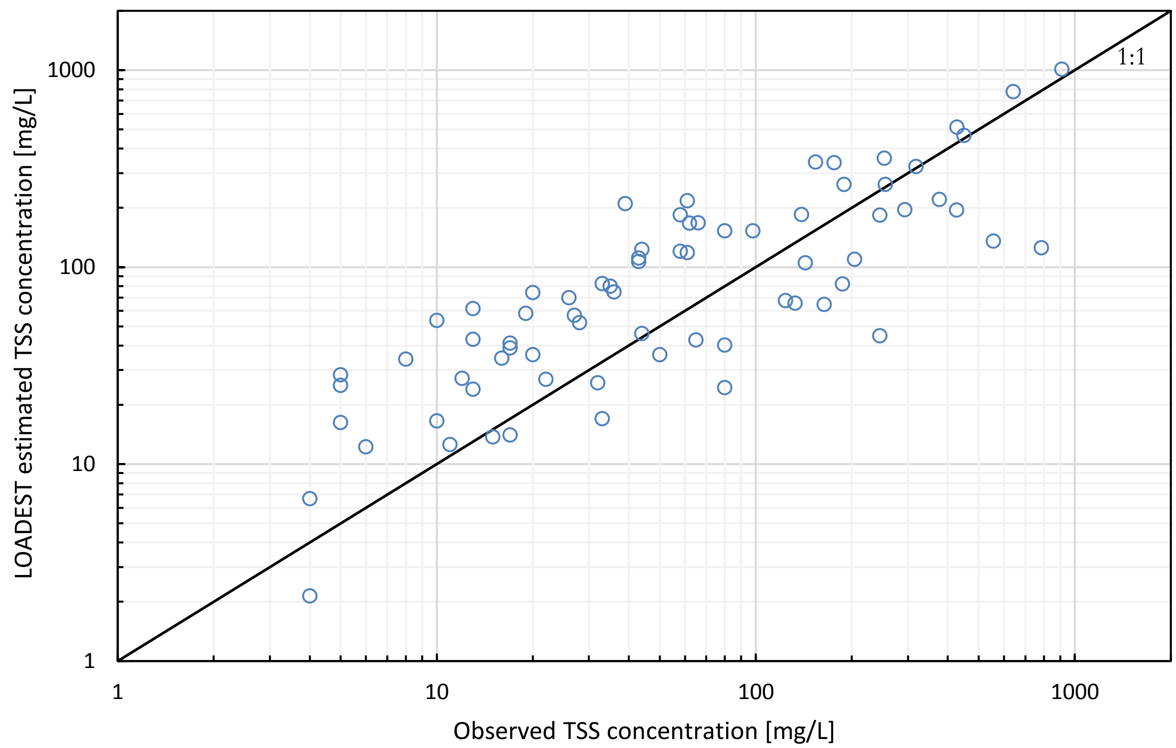

Figure 12. Observed vs LOADEST estimated suspended sediment concentrations.

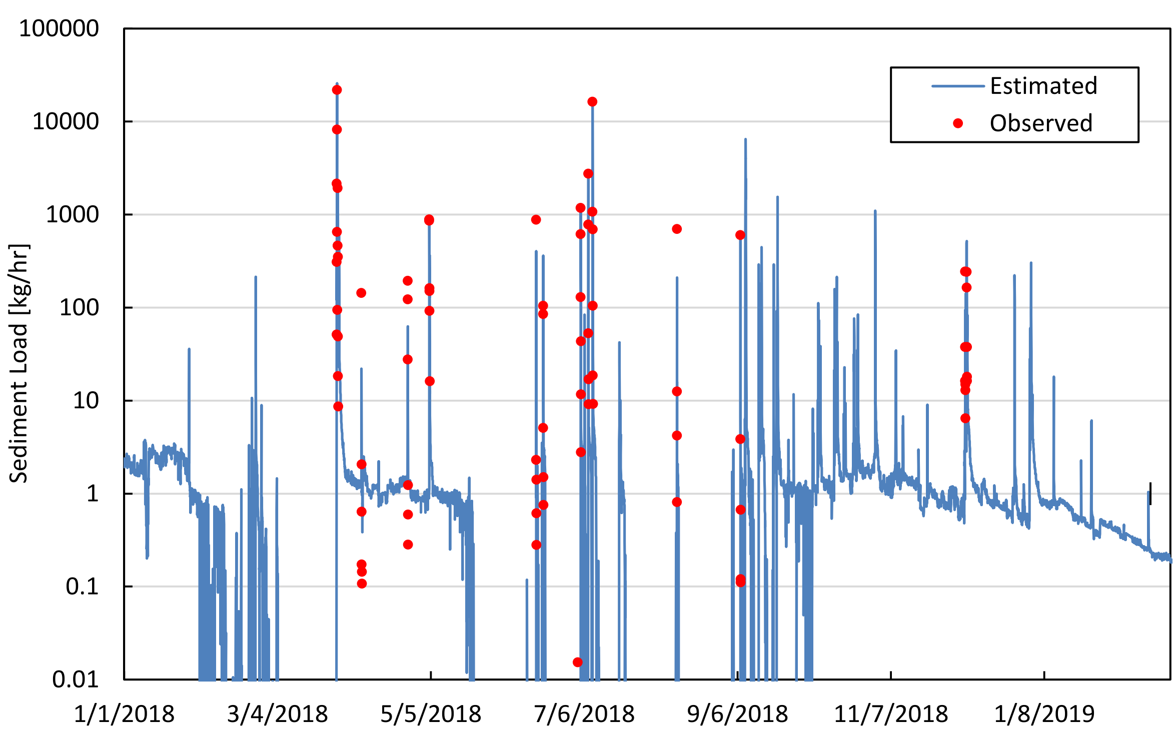

Figure 13. LOADEST estimated vs observed suspended sediment loads during the monitoring period 1 Jan 2018 to 28 February 2019.

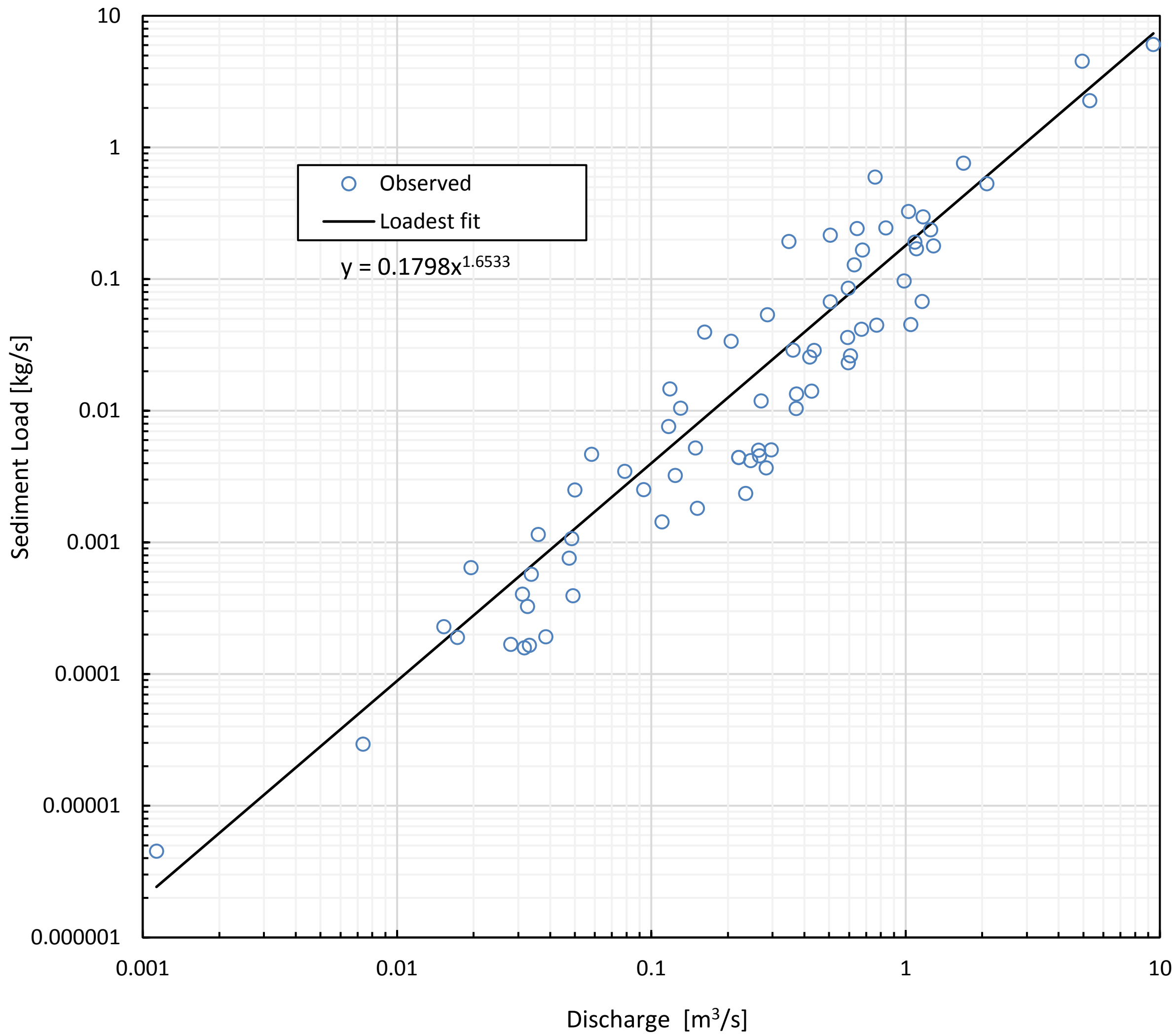

Figure 14. LOADEST rating curve for Sessom Creek sediment loads, measured as TSS. Assuming that this relationship remains unchanged in the future, estimated TSS loads may be calculated by using the above relationship and integrating across the discharge for a storm event.

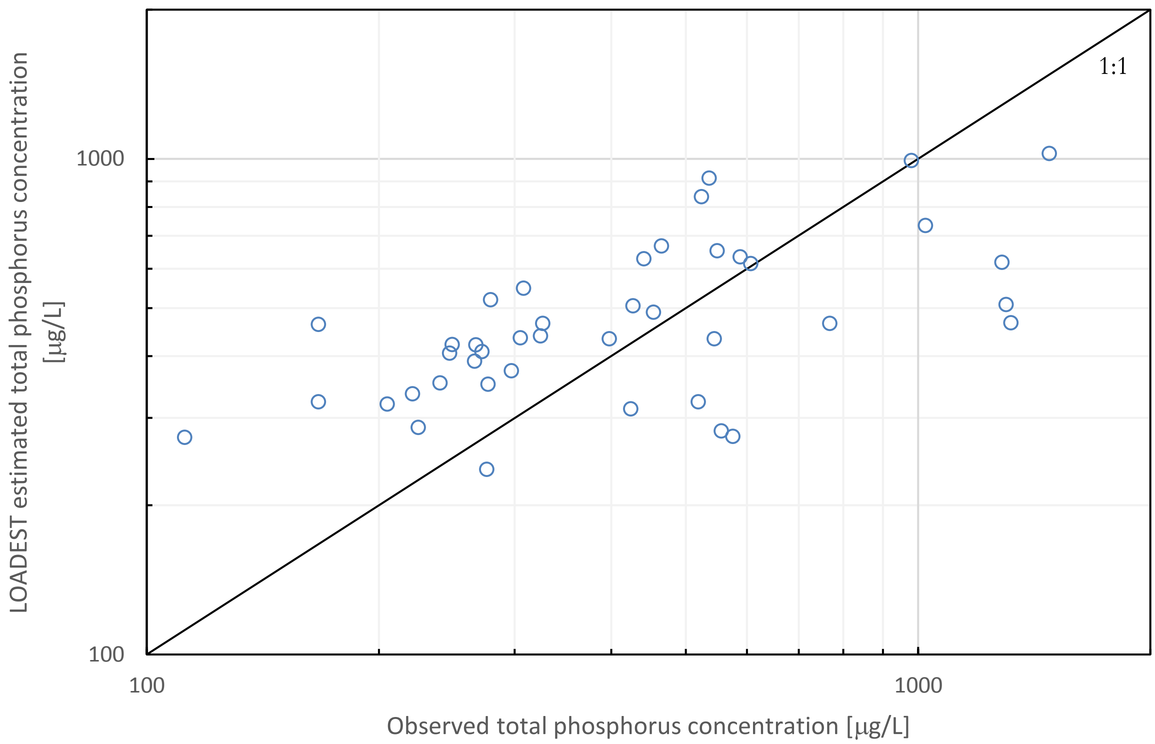

Figure 15. Observed vs LOADEST estimated total phosphorus concentrations.

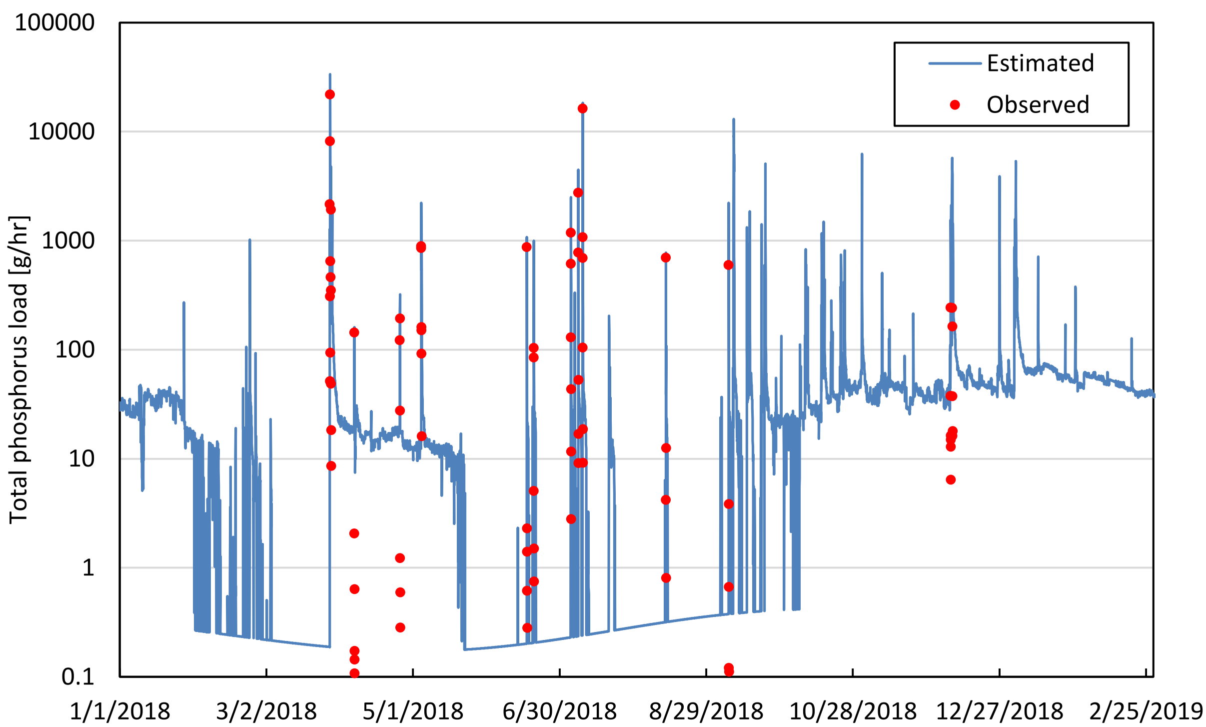

Figure 16. LOADEST estimated vs observed total phosphorus loads during the monitoring period 1 Jan 2018 to 28 February 2019.

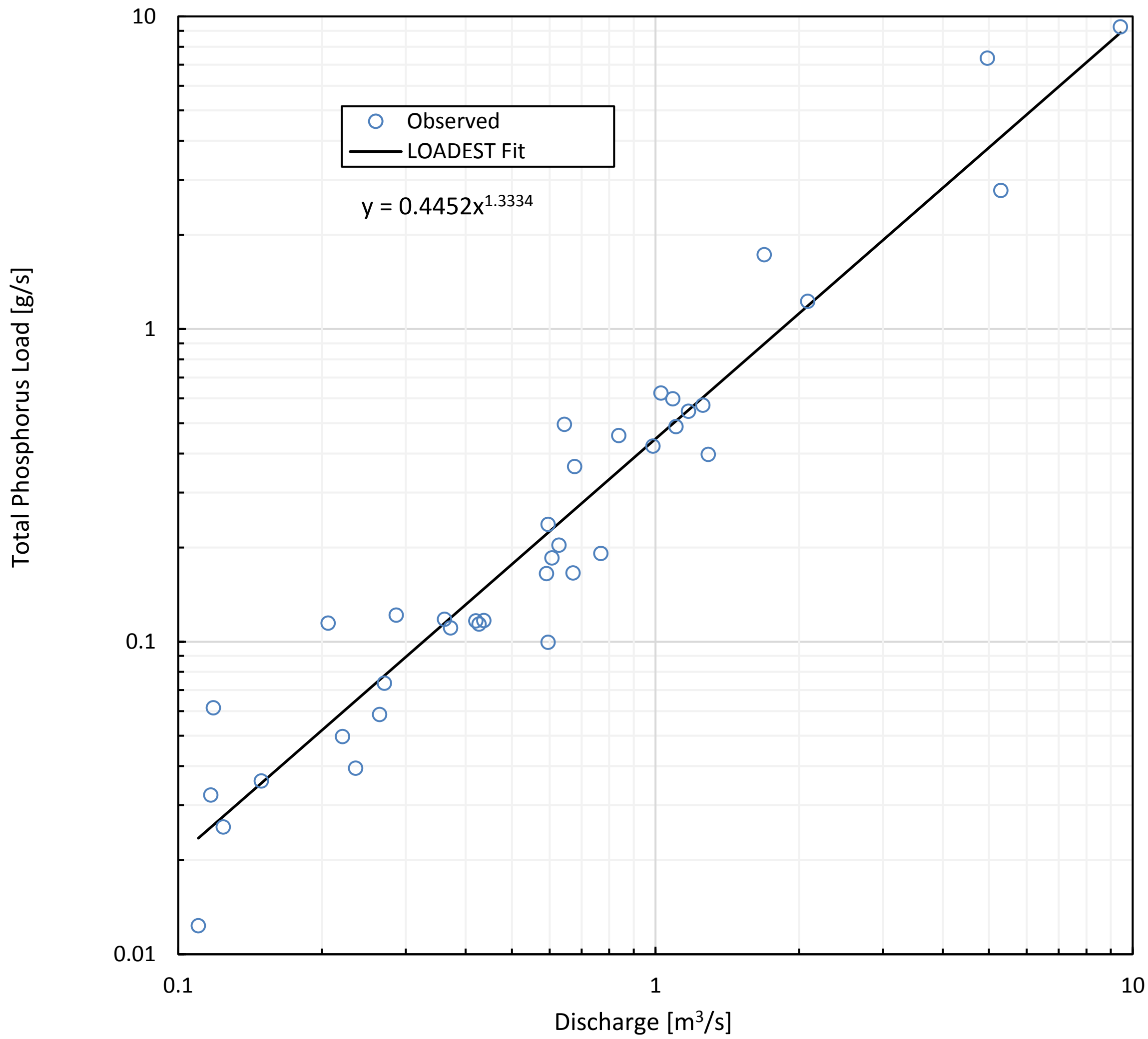

Figure 17. LOADEST rating curve for Sessom Creek total phosphorus loads.
Assuming that this relationship remains unchanged in the future, estimated TP loads may be calculated by using the above relationship and integrating across the discharge for a storm event.

Sediment loads estimated by turbidity

The observed turbidity plotted against observed suspended sediment concentration measured as total suspended solids (TSS) suggested a strong linear relationship (

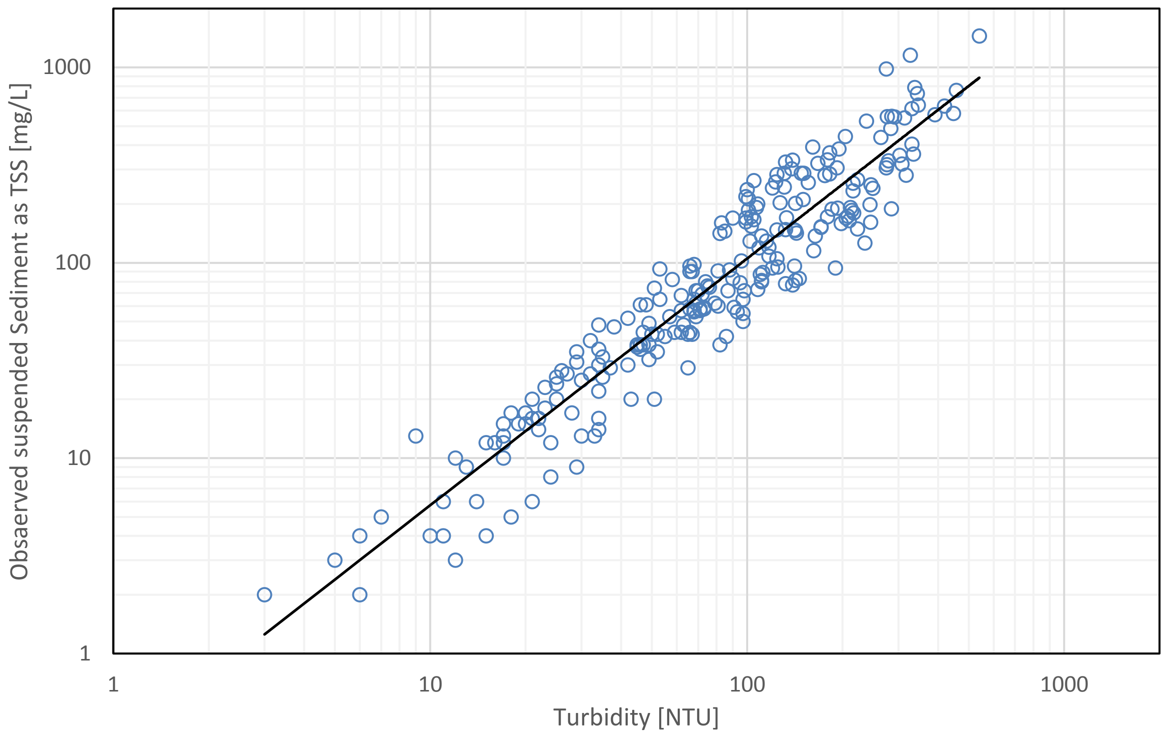

Figure 18). A regression based on 242 concurrent turbidity and concentration records was built with the USGS Spreadsheet Turbidity tool (USGS, 2010). The model calibration data set is provided in APPENDIX 4. Different combinations of untransformed and log-transformed data were examined and log-transformed TSS and turbidity were selected as the best model based on the highest adjusted R^2 value and lowest model standard percentage error (MSPE). Residuals were examined for normality and heteroscedasticity to ensure basic linear regression assumptions were met (APPENDIX 5 - Turbidity regression residual plots

The final selected TSS-Turbidity regression had the form:

$$\log_{10}(\text{TSS}) = -0.505 + 1.26 \log_{10}(\textit{Turb})$$

Where:

TSS = Suspended sediment concentration (as TSS), in milligrams per liter
Turb = Turbidity, in nephelometric units (NTU)

Regression coefficients, statistics, and bias diagnostics are shown in Table 5. Following calibration, estimated load determinations were made by summing the products of the turbidity-estimated concentrations and the measured flow volume for time interval of interest. Because the model was calculated using log-transformed data, estimated concentration values were multiplied by a calculated retransformation bias correction factor (Duan, 1983) prior to load calculation. The estimated loads resulting from the model shows good agreement with measured sediment loads (Figure 19). Figure 20 shows a rating curve for predicting sediment concentrations measured as TSS based on continuous turbidity.

Table 5. Regression coefficients, statistics and bias diagnostics for turbidity model used to estimate suspended sediment concentrations for Sessom Creek, 1 January 2018 to 28 February 2019.

Coefficients		Regression statistics and bias diagnostics			
Intercept	Log10(*Turb*)	n	Adj. R^2	MSPE [%]	Duan's Bias Correction
-0.505	1.26	242	0.89	43.7	1.09

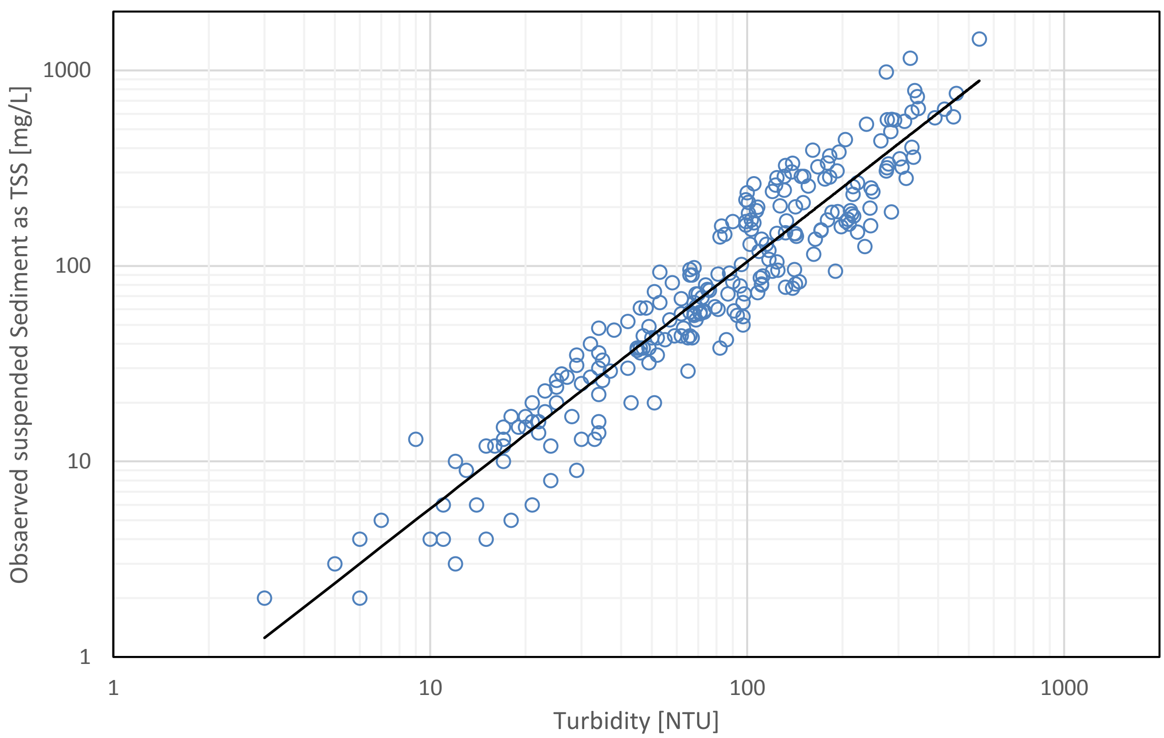

Figure 18. Turbidity vs observed suspended sediment (i.e., TSS) concentrations.

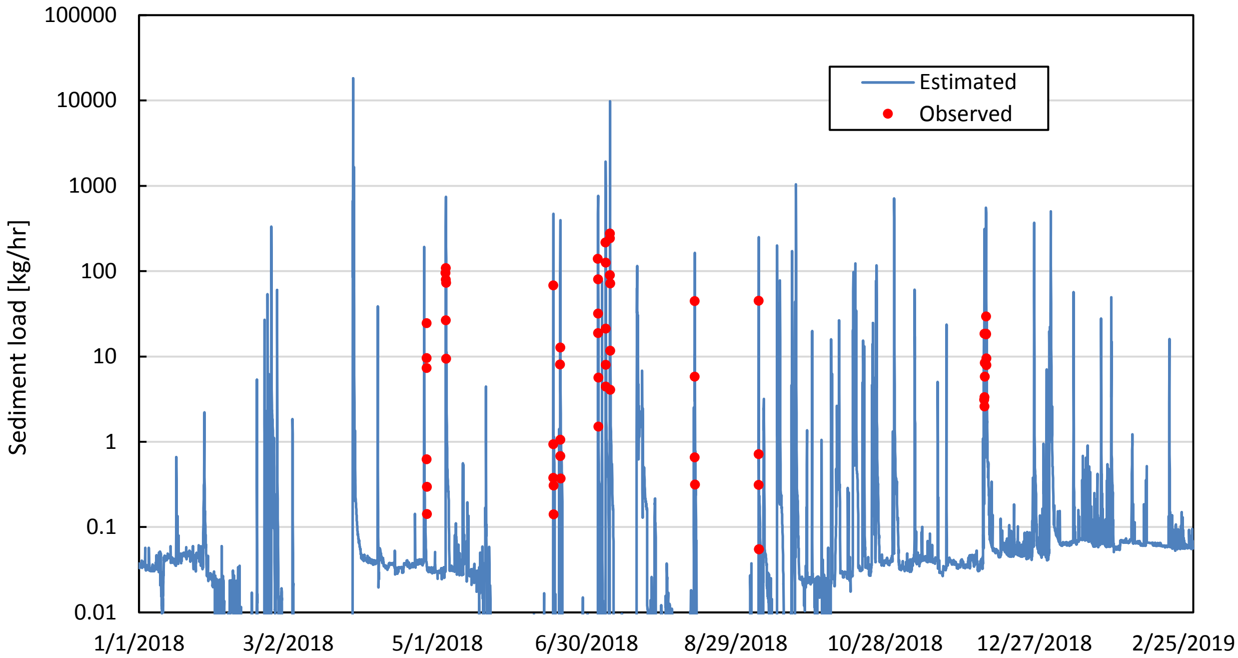

Figure 19. Sediment loads estimated by turbidity vs observed during the monitoring period 1 Jan 2018 to 28 February 2019.

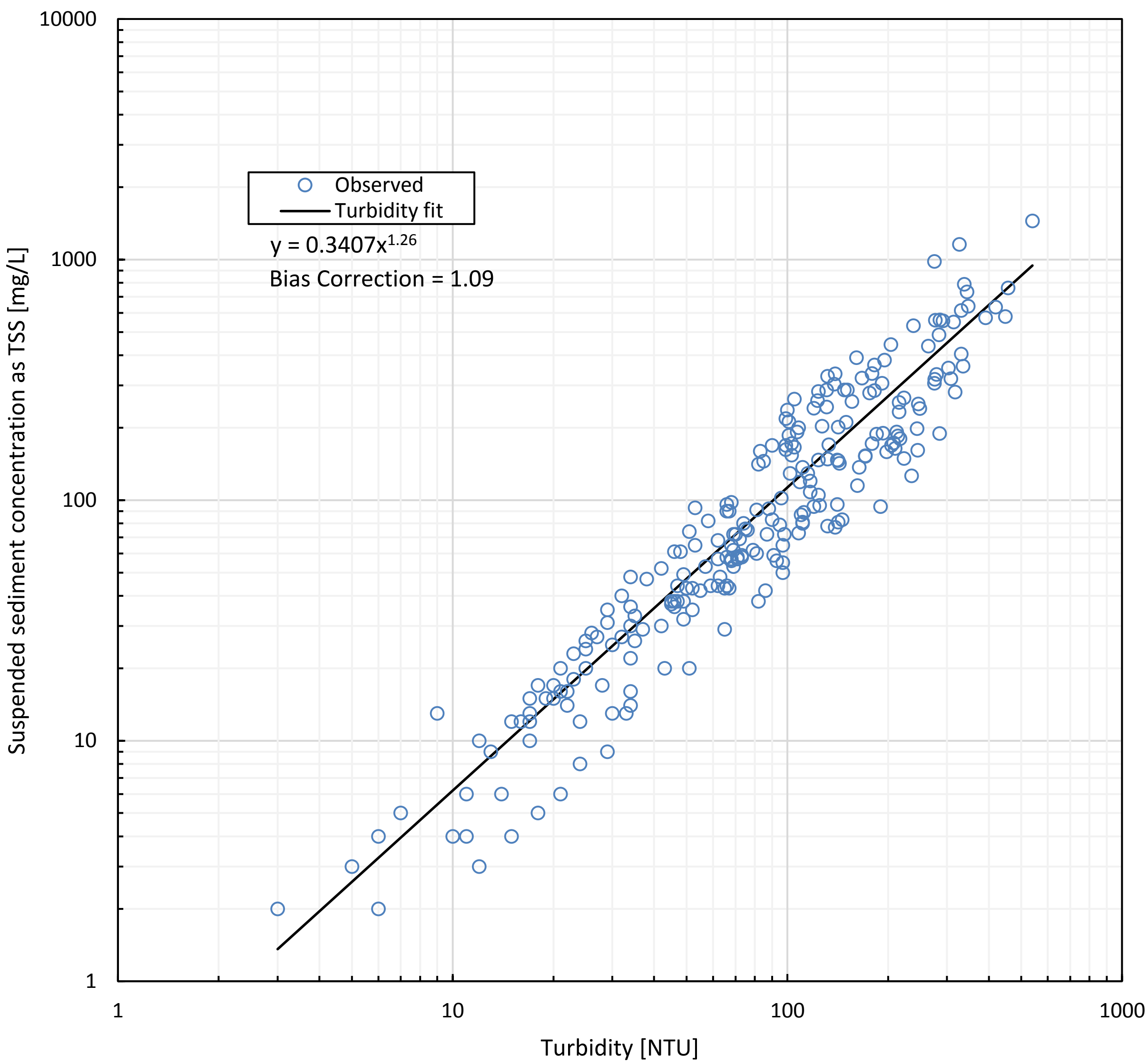

Figure 20. Rating curve for Sessom Creek suspended sediment (as TSS) concentration based on turbidity

Assuming that this relationship remains unchanged in the future, estimated TSS concentrations may be calculated during times when only turbidity data are available.

SWAT model performance

The Sessom SWAT model was calibrated and validated using daily and 15-min interval simulation outputs and measured flow and sediment data with corresponding intervals. Even though the simulation period was short, the 15-min interval model generated over 17 thousand data points and provided a sufficient sample size for statistical assessment. Both daily and 15-min models achieved excellent performance on flow and sediment yield during the calibration period, though a superior model performance of the 15-min model was visible on sediment yield estimation (Table 6). The 15-min interval outputs yielded less reliable performance over to daily comparison, due mainly to the challenges in replicating the time to peak flows and peak flow rates during dynamic storm events including the largest event in 2018 that occurred in April.

Table 6. SWAT performance statistics.

Period	Time Interval*	Sample Size	Stream Flow		Sediment Yield	
			PBIAS**	R^2	PBIAS	R^2
Calibration (Jan-June)	15min-15min	17,376	17.1	0.82	-9.9	0.83
	15min-1day	181	17.1	0.97	-1.8	0.98
	1day-1day	181	39.6	0.98	4.7	0.52
Validation (July-Dec.)	15min-15min	17,664	-6.1	0.60	-33.2	0.78
	15min-1day	184	-6.2	0.80	-32.5	0.81
	1day-1day	184	-2.5	0.73	-72.3	0.03

* Time interval: Simulation – Output
** Percent Bias (%)

The performance statistic of the daily interval model on sediment yield during the validation period was unsatisfactory. Figure 21 demonstrates that the daily model prompted a false sediment signal during an intermediate storm event occurring in October, while the 15-min model output was relatively insignificant. The false signal on sediment yield is mainly attributable to sub-daily rainfall pattern of the storm during the storm day. Sub-daily precipitation data indicate that the average rainfall intensity was low during the storm event because the storm was composed of multiple small intermittent rain events during the day. Therefore, using the daily total rainfall, the daily model overestimated rainfall intensity and overestimated soil erosion for the day and made a false signal on sediment yield. This clearly demonstrates the risk in simulating a small urban catchment with flashy stormwater drainage patterns using daily time step. As it proved more accurate than the daily model, only the 15-min model is used for the remaining analyses.

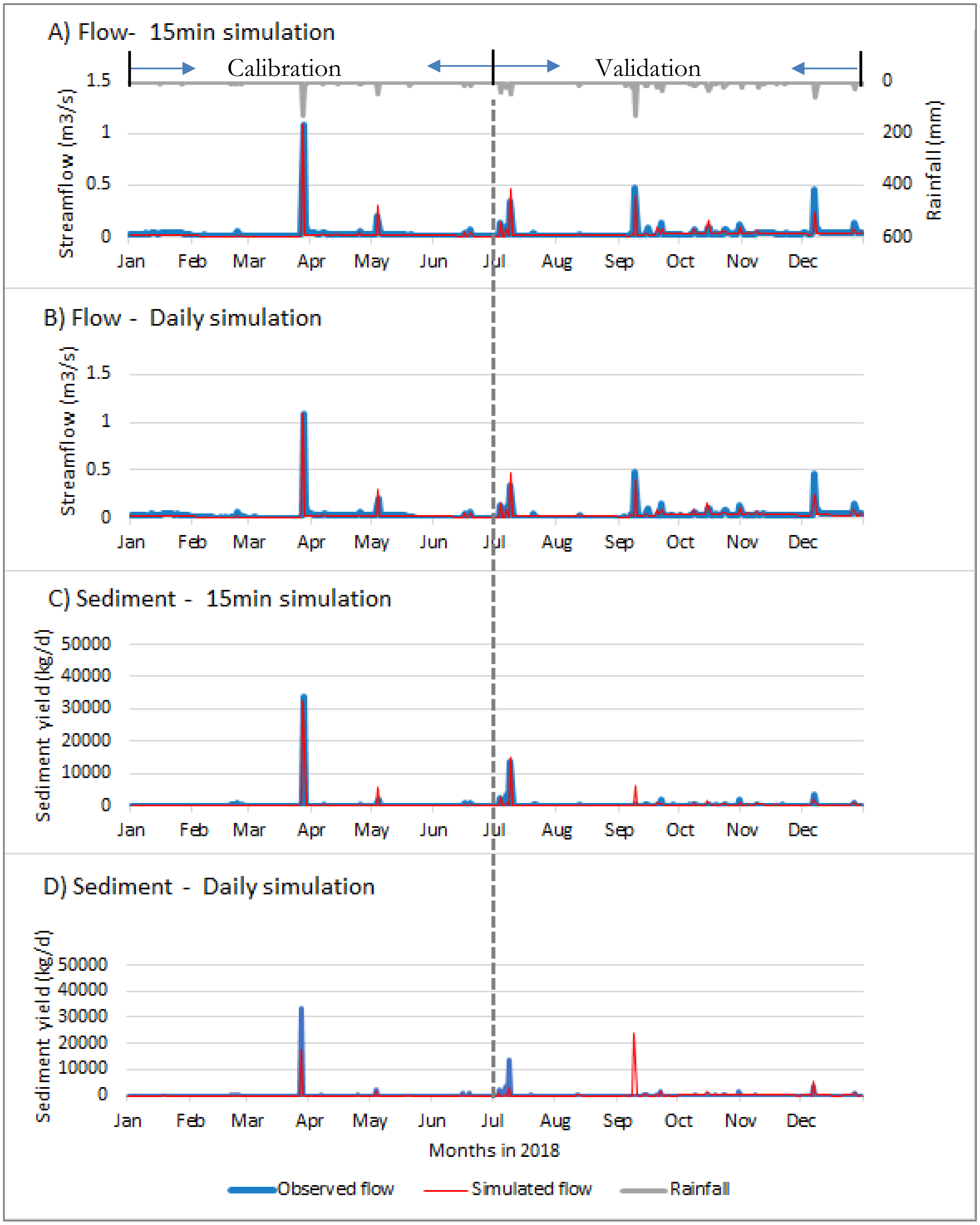

Figure 21. Calibrated daily flow and sediment yield from SWAT 15-min and daily interval models. 3A and 3C are simulated with 15-min interval and 3B and 3D are daily results.

SWAT sediment budgets and critical source areas

From watershed/river managers' perspective, it is important to identify critical source areas (CSA) of the sediment that drains into San Marcos River. In the Sessom Creek watershed, stormwater runoff hydrographs tend to be steep and short due to the high imperviousness in the watershed drainage area. The flashy stormwater runoff then provides erosive stresses to the main and tributary channels of the Sessom Creek promoting a significant bed/bank erosion. As a result, the Sessom SWAT Model suggests that sediment loads from upland erosion comprises only 20% of the total sediment loads at the watershed outlet while channel erosion claimed the majority of the sediment delivery (Figure 22). Estimation of sediment build-up and wash-off processes on pavements every 15-minute allowed for simulating first-flushes on pavements. Thus, sediment concentration in urban stormwater after first-flushes tend to reduce substantially if the storm continues during the day the storm occurs.

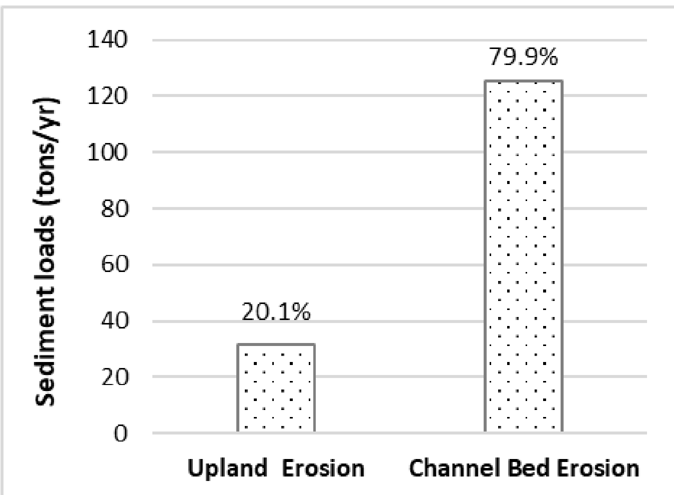

Figure 22. Origins of the sediment delivered to the watershed outlet.

A map was generated to visualize spatial variability of soil erosion in the watershed (Figure 23). Most highly eroding HRUs are on highly urbanized HRUs on steep slopes. The majority of these HRUs are close to the main channel or tributaries. Therefore, it is highly likely that these CSAs have direct impacts on sediment loads in two ways: 1) sediment yield from these HRUs contributes to channel sediment delivery, and 2) flashy stormwater runoff from these HRUs accelerate channel bed/bank erosion. Stormwater best management practices (BMP) must be implemented in these eroding areas to alleviate soil losses, channel erosion, and water contamination.

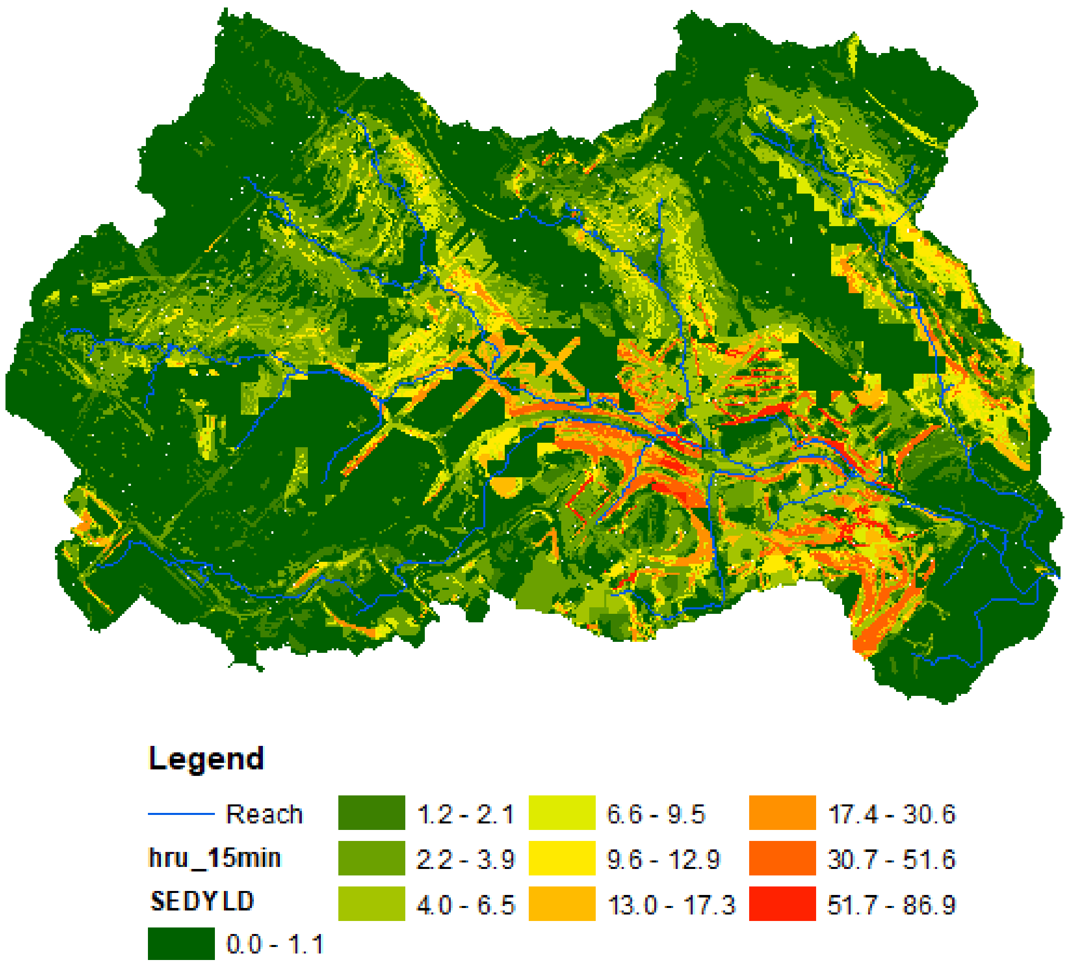

Figure 23. Modeled annual soil erosion rate by HRU (metric tons/ha).

BMP scenario: proposed detention pond

The calibrated 15-min SWAT model was used to evaluate the efficacy of a detention pond on controlling peak flow and sediment delivery from Windmill tributary. In the SWAT model, a detention pond is a structural BMP that can be placed in channels to detain channel flow temporarily during and after a storm event. Discharge in the modeled pond is controlled by either or a combined stepped weir system and circular orifice holes on a concrete wall that blocks the channel. In this scenario, a stepped weir system was designed to provide approximately 70% or more reduction of peak flow rates. Result indicates that the detention pond provides a significant attenuation of peak flows in the Windmill tributary during high flow events as depicted in Figure 24. The reduction in peak flow rate was greater for high peaks and lower for smaller storm events. For example, multiple storm events on March 27, 2018 with the peak flow rate of over 1.5 m^3/s of the first storm of the day would have been reduced to less than 0.3 m^3/s after the construction of the detention pond. With extended detention, drainage time was extended to over 24 hours from less than four hours.

The sediment reduction rate in the detention pond discharge flow was 18.2%. At the Sessom Creek watershed outlet, the model output suggests that only 13.5% reduction of sediment yield is expected with the Windmill detention pond.

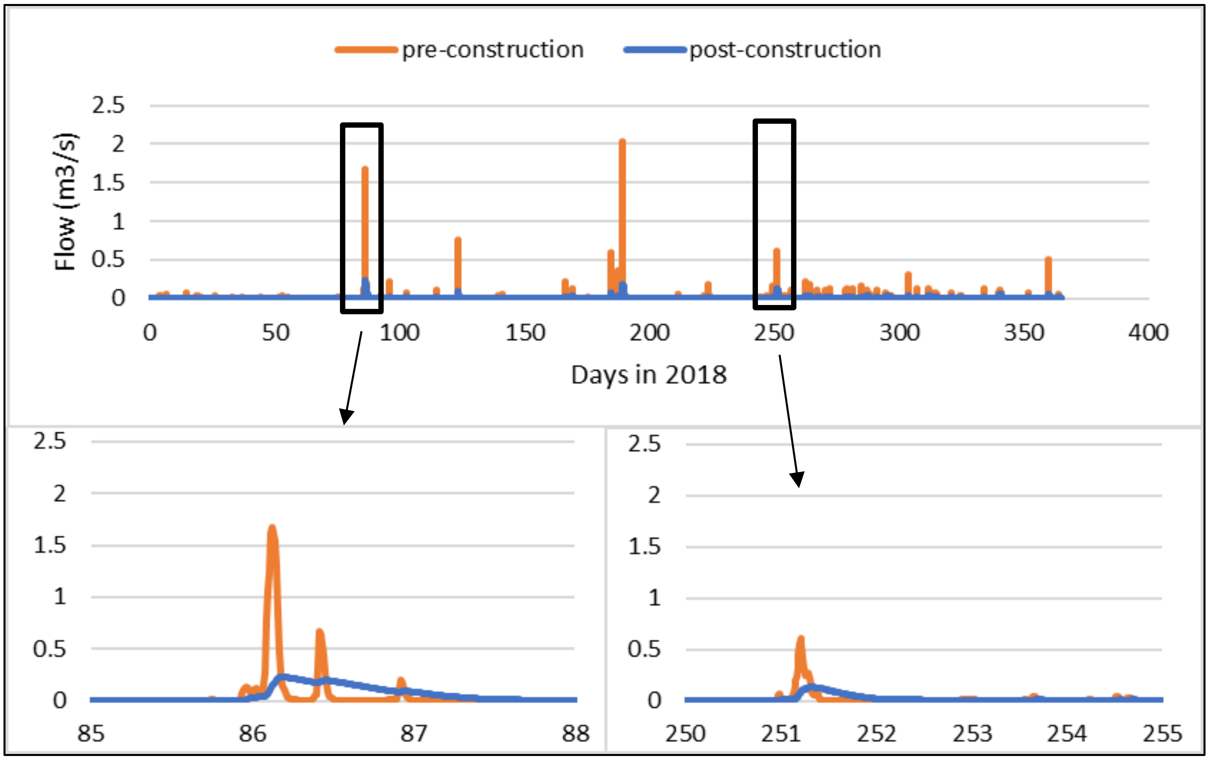

Figure 24. Modeled channel flow at the outlet of Windmill tributary comparing pre- and post-construction of a proposed detention pond.

NPS Concentrations vs. Discharge

Concentrations of nutrients and sediments varied greatly between and within storm events. Figure 25 to Figure 30 illustrate variations in NPS concentrations with respect to discharge during the sampling period.

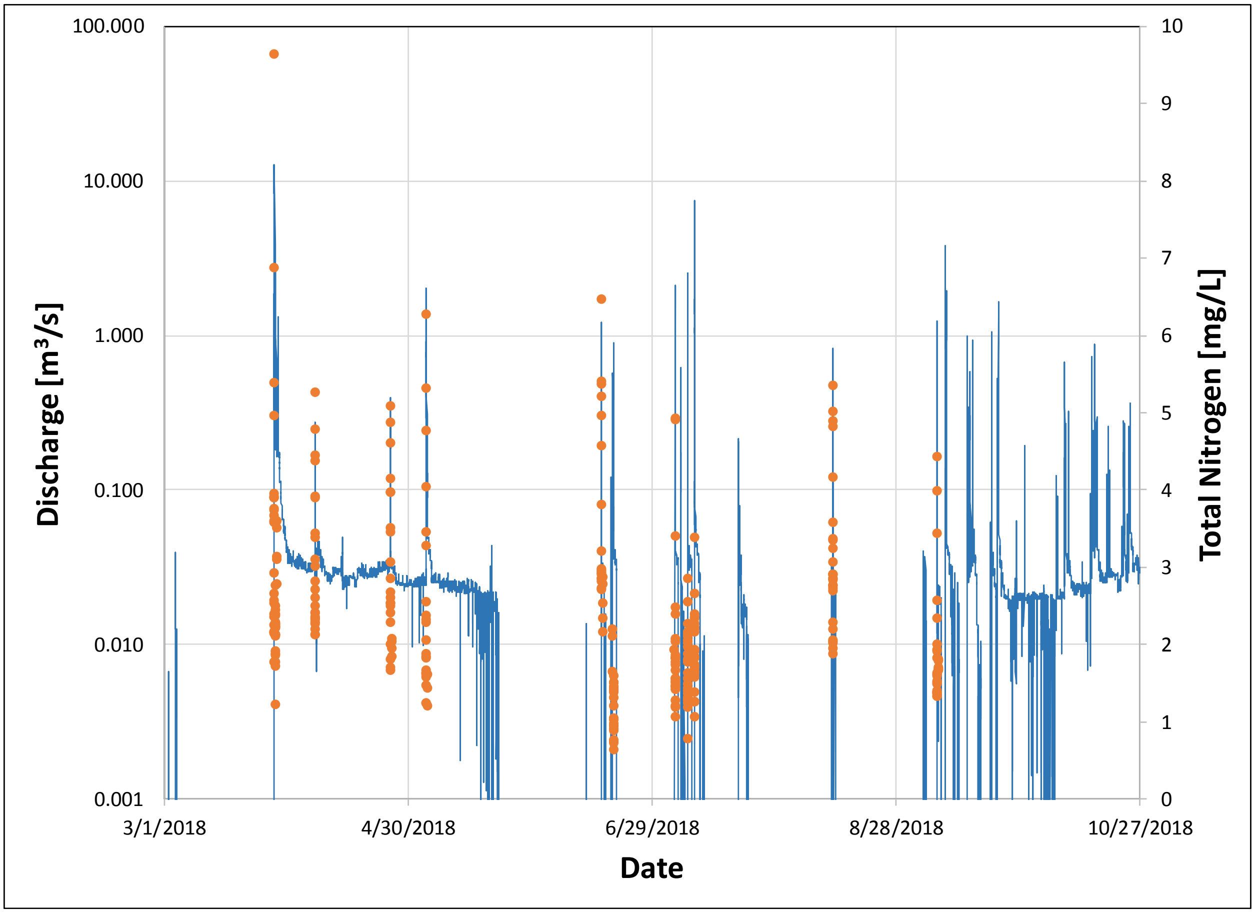

Figure 25. Total Nitrogen concentrations in stormwater samples.
Note that the NPS axis is linear, while the discharge axis is logarithmic.

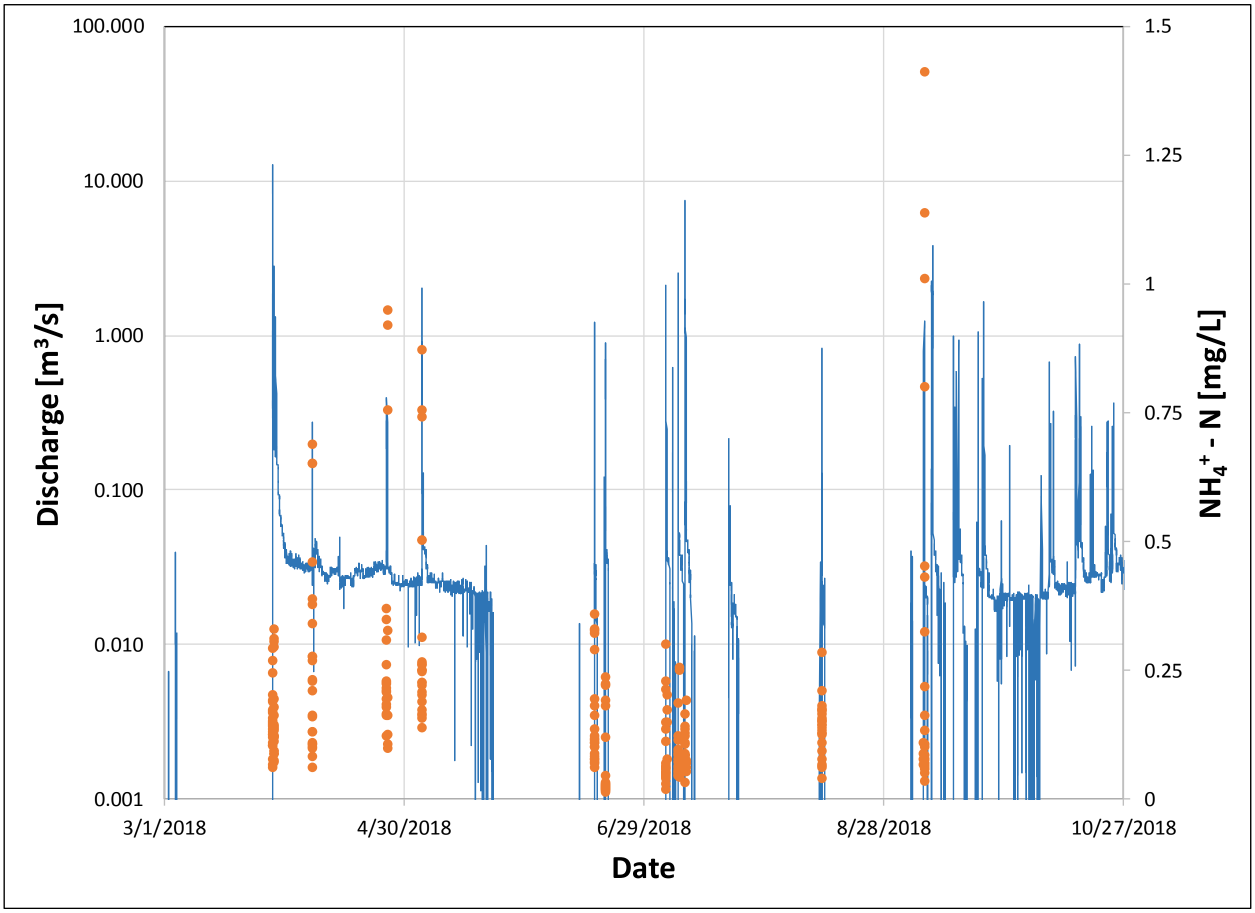

Figure 26. Ammonium as Nitrogen (NH_4^+-N) concentrations in stormwater samples. Note that the NPS axis is linear, while the discharge axis is logarithmic.

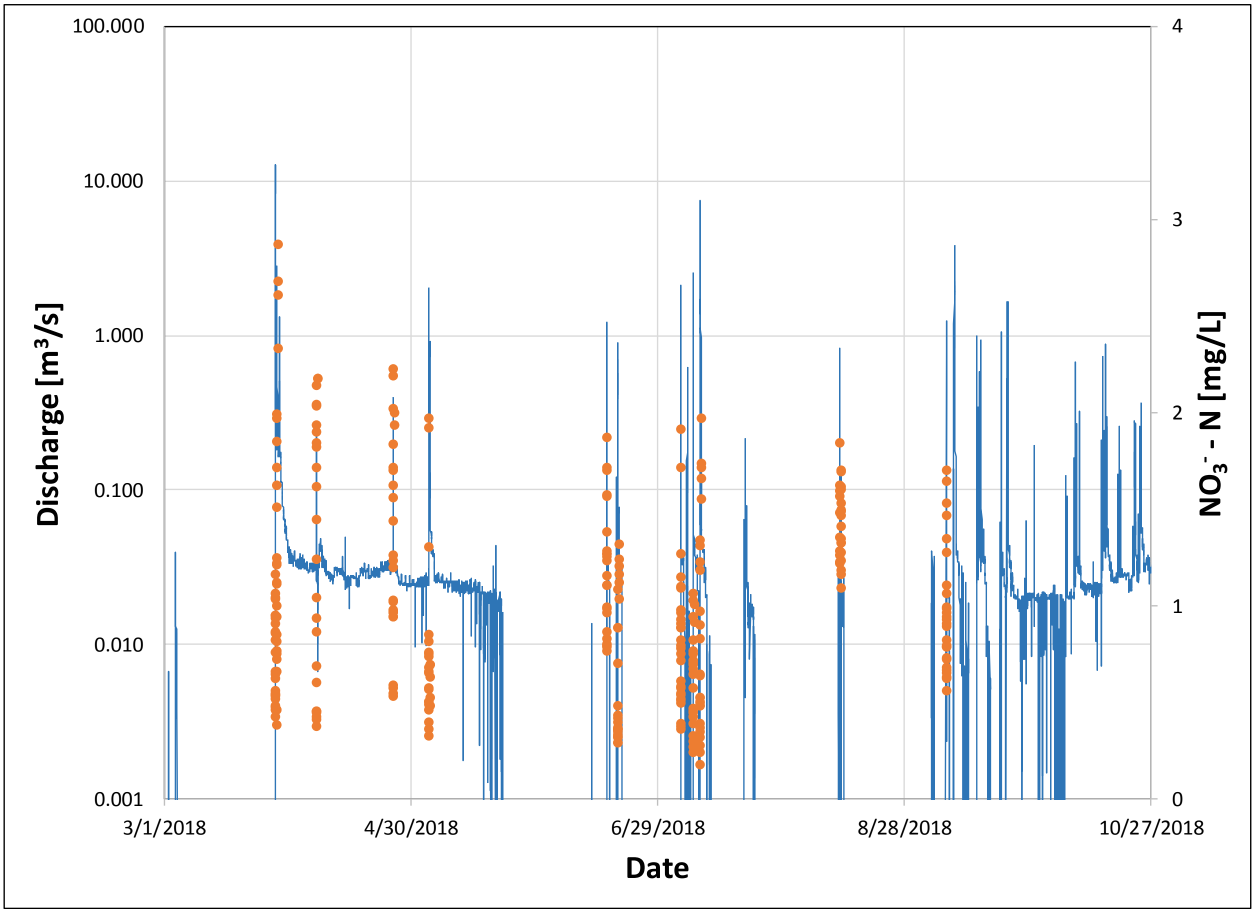

Figure 27. Nitrate as Nitrogen (NO_3^--N) concentrations in stormwater samples.
Note that the NPS axis is linear, while the discharge axis is logarithmic.

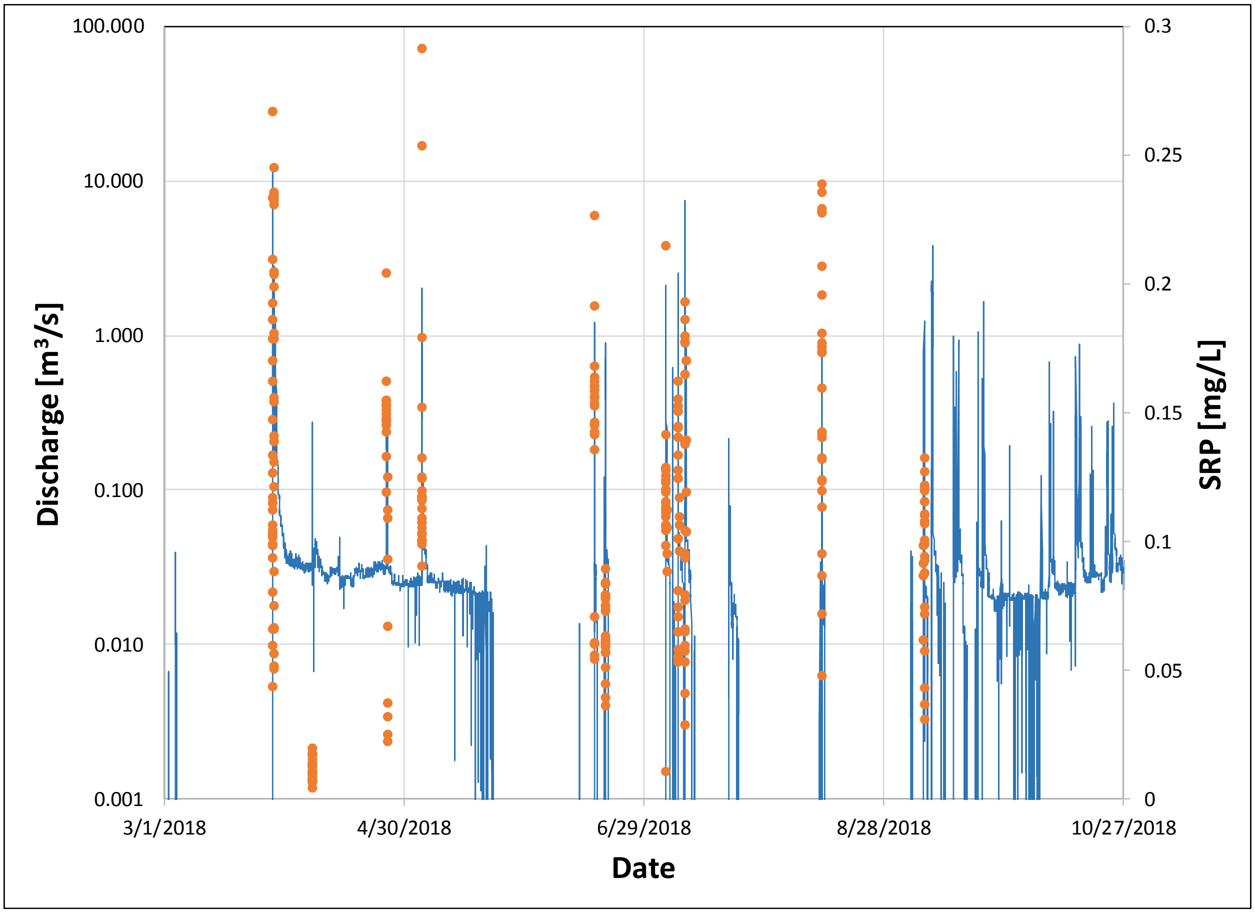

Figure 28. Soluble Reactive Phosphorous (SRP) concentrations in stormwater samples. Note that the NPS axis is linear, while the discharge axis is logarithmic.

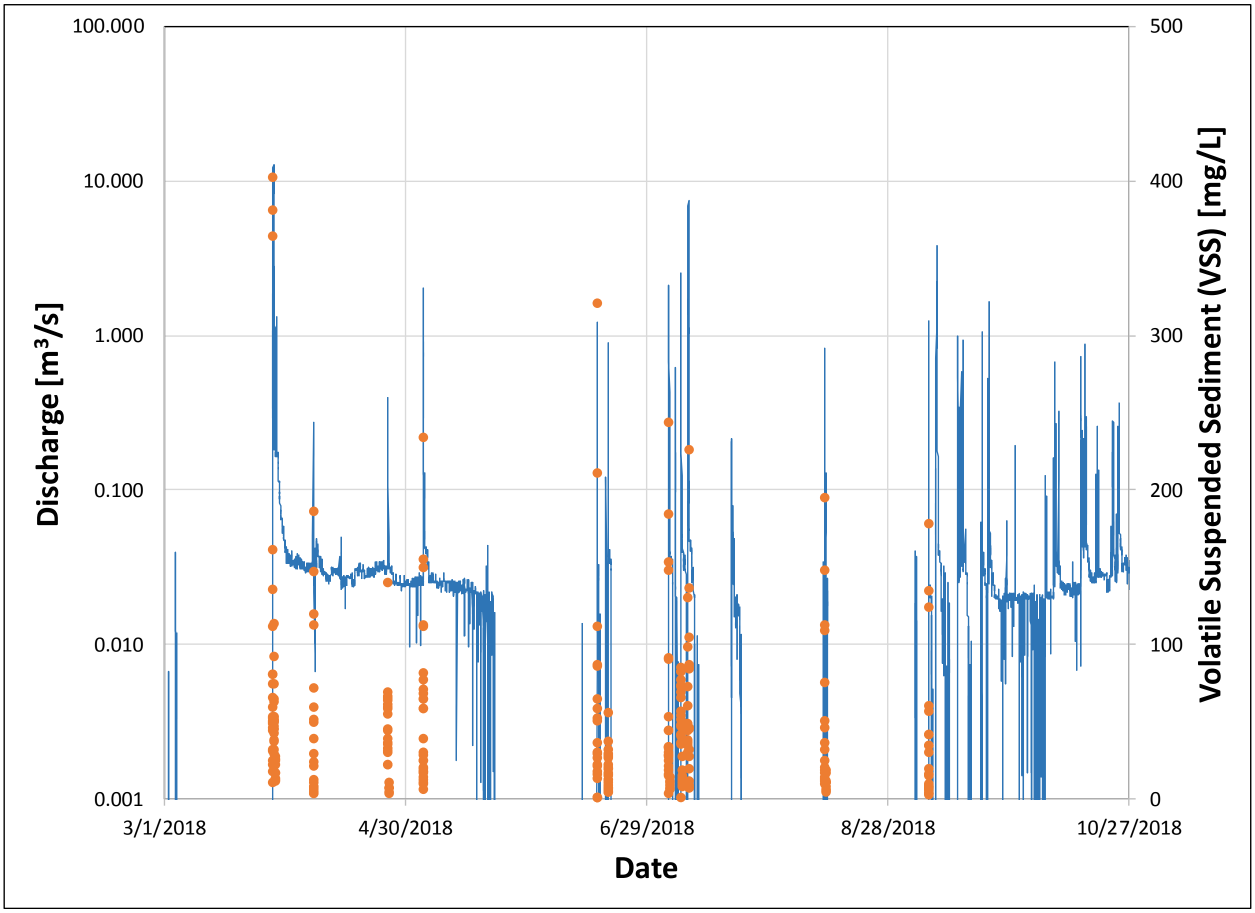

Figure 29. Volatile Suspended Sediments (VSS) concentrations in stormwater samples.
VSS is the organic portion of Total Suspended Sediments (TSS). Note that the NPS axis is linear, while the discharge axis is logarithmic.

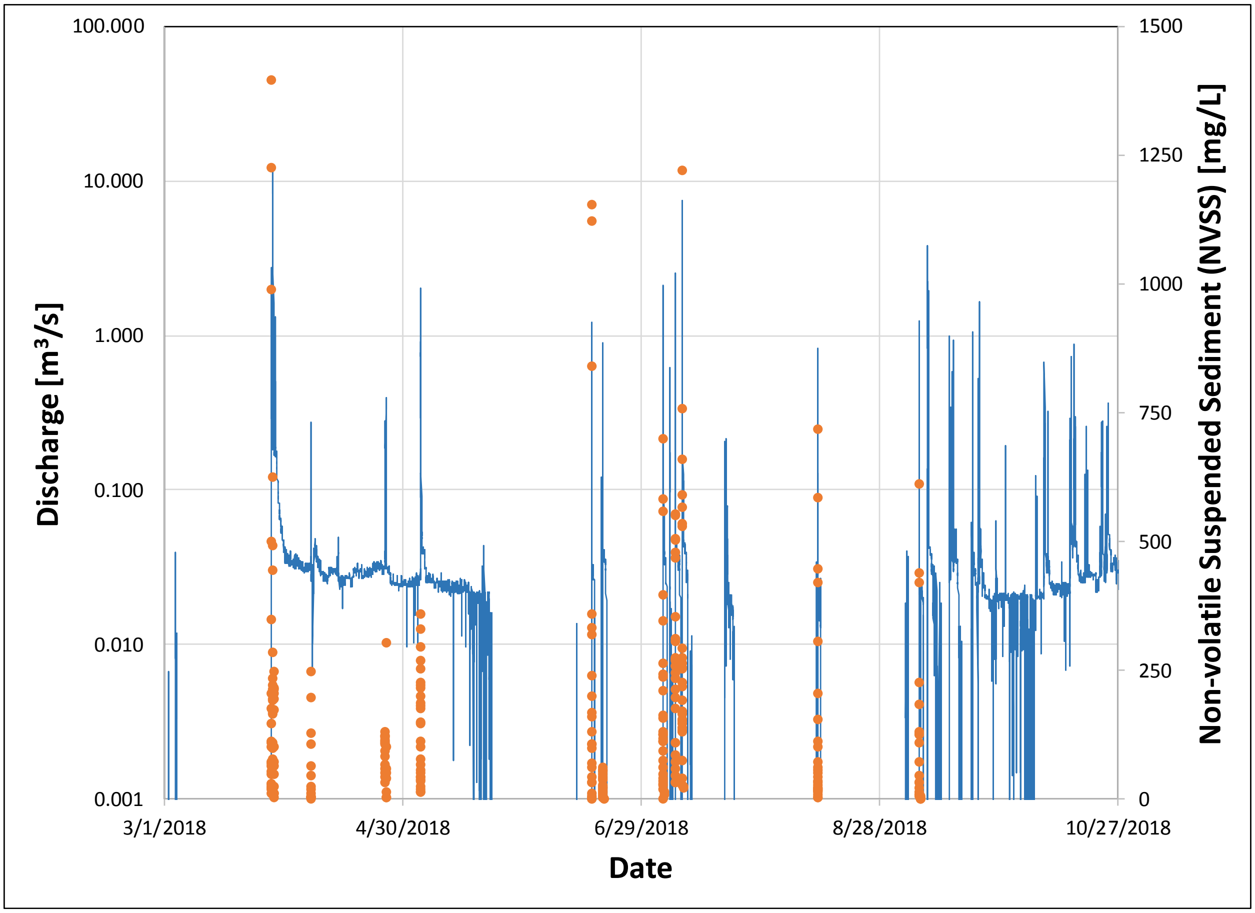

Figure 30. Non-volatile Suspended Sediments (VSS) concentrations in stormwater samples. NVSS is the inorganic portion of Total Suspended Sediments (TSS), and represents mineral grains and other non-organic sediments. Note that the NPS axis is linear, while the discharge axis is logarithmic.

EMC Data

Event Mean Concentrations (EMC) for each parameter during 12 fully-sampled storm events were calculated by dividing the total event-load for each event by the corresponding total discharge for that event (Table 7). EMCs were not calculated for bacteria, because many of the analyses returned results that were greater than the maximum quantifiable value using the dilutions that were chosen at the start of analysis for each event. Because holding times should be limited (we began analysis as soon as practical after sampling was completed), the methodological time required to quantify the number of bacteria in each sample is 24 hours, and each storm event resulted in different and unpredictable concentrations, actual bacterial counts were often too high to quantify, but *E. coli*. Counts ranged from ~500 MPN/100 mL to >120,000 MPN/100 mL.

EMCs provide an average event concentration that may be used to estimate loads in un-sampled storm events, assuming that discharge is known. Although this method provides a less accurate value that modeling or sampling might, it does allow a gross estimate of loads to be made (Figure 31)

Table 7 Summary of sediment and nutrient EMCs for each storm event.

E	Day [mm/dd/yy]	EMC TSS [mg/L]	EMC VSS [mg/L]	EMC NVSS [mg/L]	EMC TN [mg/L]	EMC TP [mg/L]	EMC NH_4^+N [mg/L]	EMC SRP [mg/L]	EMC NO_3^-N [mg/L]
1	03/28/2018	544.54	95.07	449.47	2.34	0.83	0.17	0.18	0.82
2	03/28/2018	157.35	35.15	122.2	2.13	0.40	0.13	0.14	1.12
3	04/07/2018	134.78	65.16	69.62	3.15	0.33	0.20	0.01	0.83
4	04/25/2018	105.59	39.06	66.53	2.03	0.25	0.17	0.08	0.76
5	05/04/2018	136.45	36.12	100.33	1.69	0.32	0.21	0.10	0.51
6	06/16/2018	37.68	15.06	22.62	0.42	0.08	0.01	0.02	0.12
7	06/19/2018	39.48	16.98	22.50	0.87	0.14	0.03	0.05	0.35
8	07/04/2018	166.67	35.87	130.80	1.53	0.37	0.07	0.09	0.58
9	07/07/2018	395.59	55.86	339.73	1.67	0.86	0.06	0.07	0.44
10	07/09/2018	611.02	97.87	513.15	2.09	0.83	0.06	0.10	0.63
11	08/12/2018	296.86	63.04	233.82	2.62	0.69	0.07	0.10	0.95
12	09/07/2018	190.85	43.83	147.02	1.80	0.41	0.10	0.08	0.69

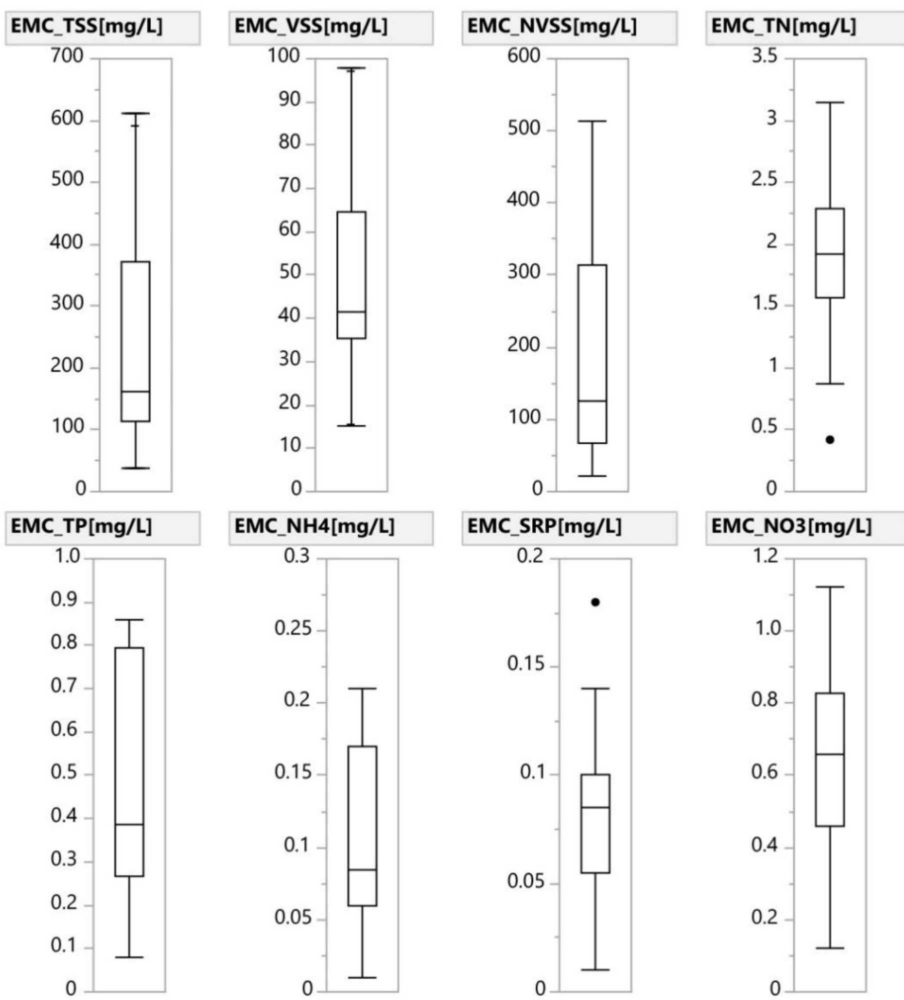

Figure 31. Box and whisker outlier plots of EMCs for 12 storm events. Mean and quartiles are illustrated.

EMC Analyses: linear relationships with environmental parameters

Event Mean Concentrations (EMC) for analyzed water quality parameters (NPS constituents) were calculated for each of the 12 storm events, and simple linear regression models were used to explore potential relationships between EMCs and environmental and physical parameters, in an attempt to better understand processes that may be influencing both the concentrations and transport of NPS pollutants during storm events, as well as relationships that may provide information that could be useful for informing management decisions.

Data for all analyzed parameters are included in APPENDIX 6 – Tables of measured parameters for 12 storm events. Summaries of these parameters are illustrated in Table 8

Selection of the best predictors explaining EMCs was based on R^2 and p values, and key variables derived from PCA of the environmental and antecedent conditions, in addition to investigating relationships between different water quality parameters. Table 9 illustrates correlations between all measured or calculated environmental parameters that were used in regression models, or PCAs. These simple correlations were used to both remove variables with significant co-variation, as well as to explore the data.

Table 8 Summary of environmental variables for each storm event.
Day (mm/dd) of 2018, Total rain (Rain), total runoff (RO), duration of the rainfall (Rain Dur.), average intensity of the rainfall (Rain Int.), number of Antecedent Dry Days (ADD), Maximum Rain Intensity (Max RI), Peak Discharge (PQ), accumulated evapotranspiration in the last 8 and 2 weeks (ETp8 and ETp2), and accumulated rain in the previous 1 and 2 weeks (Rain 1 and Rain 2).

E	Day (mm/dd/yy)	Rain (mm)	RO (m^3)	PQ (m^3/s)	Rain Dur (min)	Rain Int. (mm/hr)	Max RI (mm/hr)	ETp8 (mm)	ETp2 (mm)	Rain1 (mm)	Rain2 (mm)	ADD
1	03/28/18	132.6	66472	13.3	412	19.3	118.9	147.9	56.32	0.0	0.3	8
2	03/28/18	33.0	14985	3.3	158	12.5	76.2	147.9	56.32	132.6	132.8	0
3	04/07/18	5.6	1274	0.9	15	22.4	27.4	167.1	52.1	0.0	182.9	8
4	04/25/18	13.5	2597	0.3	215	3.8	9.1	201.2	58.6	0.3	2.0	3
5	05/04/18	64.8	14667	2.0	318	12.2	125.0	206.7	50.77	0.0	13.7	8
6	06/16/18	15.2	23257	1.2	35	26.1	67.1	291.2	86.5	0.0	0.0	19
7	06/19/18	21.3	4502	1.2	185	6.9	12.2	294.4	81.88	15.8	15.8	0
8	07/04/18	56.6	11268	2.6	160	21.2	82.3	317.4	80.29	0.0	25.4	8
9	07/07/18	27.7	8621	3.4	60	27.7	125.0	315.9	92.35	66.6	67.6	0
10	07/09/18	81.8	28095	9.0	290	16.9	173.7	312.6	81.2	96.0	97.0	0
11	08/12/18	11.9	1844	1.2	145	4.9	42.7	309.5	76.8	0.0	0.0	31
12	09/07/18	12.2	2823	1.4	90	8.1	33.5	315.0	71.18	6.4	6.4	2

Table 9 Correlation Matrix between environmental and antecedent conditions.
E1 and E2 were excluded due to some missing data. P values were obtained through permutations.

	Rain	RO	Peak Q	Rain Dur	Rain Int.	Max RI	ETp8	ETp2	Rain1	Rain2	ADD
Rain	**1.00**	0.47	0.57	0.65*	0.14	0.72*	-0.03	-0.12	0.11	-0.14	-0.18
RO	0.47	**1.00**	0.42	0.04	0.51	0.60*	-0.04	0.16	0.26	-0.11	0.08
Peak Q	0.57	0.42	**1.00**	0.00	0.45	0.78**	0.06	0.22	0.74*	0.29	-0.33
Rain Dur	0.65*	0.04	0.00	**1.00**	-0.60*	0.16	-0.21	-0.4	-0.06	-0.41	-0.12
Rain Int.	0.14	0.51	0.45	-0.60*	**1.00**	0.55*	0.12	0.36	0.12	0.38	-0.04
Max. RI	0.72*	0.60*	0.78**	0.16	0.55	**1.00**	0.07	0.13	0.33	0.04	-0.05
ETp8	-0.03	-0.04	0.06	-0.21	0.12	0.07	**1.00**	0.87**	-0.35	-0.64	0.26
ETp2	-0.12	0.16	0.22	-0.4	0.36	0.13	0.87**	**1.00**	-0.05	-0.42	0.16
Rain1	0.11	0.26	0.74*	-0.06	0.12	0.33	-0.35	-0.05	**1.00**	0.49	-0.44
Rain2	-0.14	-0.11	0.29	-0.41	0.38	0.04	-0.64	-0.42	0.49	**1.00**	-0.30
ADD	-0.18	0.08	-0.33	-0.12	-0.04	-0.05	0.26	0.16	-0.44	-0.30	**1.00**

* indicates p value <0.05
** indicates p value <0.01
Absence of asterisk implies non-significant correlation

The twelve sampled storm events include a range of sizes, intensities, and antecedent conditions. This provided an opportunity to explore simple linear relationships between EMCs as a response, and a variety of possible physical and environmental predictor variables (Table 10).

The best predictor of TSS EMCs was Peak Q ($R^2 = 0.83$, p value < 0.0001). TP EMCs were strongly correlated with TSS ($R^2 = 0.88$, p value < 0.0001), and TN with VSS ($R^2 = 0.46$, p value = 0.01). For dissolved nutrients, the more significant predictor for SRP was rain duration, while ETp2 was significant for NH_4^--N and NO_3^-N.

RO, Peak Q, Max RI, and TSS are highly correlated with each other. The intercept was forced through the origin when RO and Peak Q were used as predictors because it can be assumed that any concentration of NPS pollutant will be "0" when there is not runoff or discharge. However, this inflated the R^2, p value, and residual standard error of the models.

Table 10. Best regression models to estimate EMCs.
All storm events are included.

Y	Predictor	Equation	ε	F	R^2	p value
TSS	Peak Q	TSS = (54.26* Peak Q)	126.8	54.58	0.83	<0.0001
TP	TSS	TP = 138 + (1.36*TSS)	98.29	76	0.88	<0.0001
TN	VSS	TN=934.73+(18.58*VSS)	562.2	8.56	0.46	0.015
SRP	Peak Q	SRP= (15.9* Peak Q)	56.65	23.56	0.68	0.0005
NH_4^+-N	ETp2	NH4 = 405 + (-4.25*ETp2)	23.05	7.45	0.89	<0.0001
NO_3^--N	ETp2	NO3=1430 + (-11.09*ETp8)	232.3	5.432	0.35	0.042

DF = 10, for all models, except for RO and Peak Q, which was 11.
ε= residual standard error
Note: Intercept was forced to the origin when using RO and Peak Q as predictors.

Peak Q and Max. RI were the environmental factors of most importance for total event loads and EMCs of TSS, TN, and TP. Antecedent rain was a weak predictor of TN and TP loads, but not for TN and TP EMCs. These results coincide with results found by Gellis (2013) where Peak Q was a significant predictor for both loads and EMCs. However, that study sampled >100 storm events and found that the magnitude of loads and EMCs of sediments in an urban watershed in Puerto Rico was dependent on both antecedent conditions (previous rain) and total rainfall, while in this study these predictors were either weak or non-significant as predictor variables. This could be the result of differences in processes operating in the watershed, or it could be due to a relatively low number of events included in my data.

Results suggest that total and dissolved forms of Nitrogen are highly dependent on VSS, and TP can be predicted using TSS, which explains the high values of particulate P and N (total – dissolved) relative to dissolved fractions. Models developed by Wang, et al. (2011) showed that total runoff and ADD were significant predictors for TSS and other NPS in a small urban watershed. Although we hypothesized that antecedent conditions might play a significant role in the generation of loads and concentrations of sediments and nutrients, results support this idea only with some predictors in a few response variables. For example, accumulated potential evapotranspiration during the two weeks prior each event (ETp2) was only significant when explaining NH_4^+-N and NO_3^--N. The relationship between NH_4^+-N and ETp2 can be explained by the nitrogen cycle. NH_4^+-N (and less so for NO_3^--N) is the form of N consumed by plants and microorganism in the soil. While actual evapotranspiration (ETa) is a process that include evaporation and plant transpiration, ETp is more related to atmospheric demands. Once NH_4^+-N or NO_3^--N are taken up by plants, transformation to N_2 occurs (atmospheric nitrogen), and this is released to the atmosphere through transpiration (Kalf, 2002). This process likely explains the strong negative relationship between EMCs of NH_4^+-N and ETp2 (**Error! Reference source not found.**). ETp can be very different from ETa in dry times or regions, because plants limit their transpiration in dry conditions when demand and potential for evapotranspiration are still high. However, the sampling period occurred generally during wet conditions (10 of the 12 storm events had ADD of 8 or less days). Therefore, it is possible that the vegetation in Sessom Creek was not water-limited, and that active evapotranspiration and nutrient uptake played an important role in nitrogen forms and availability during storm events.

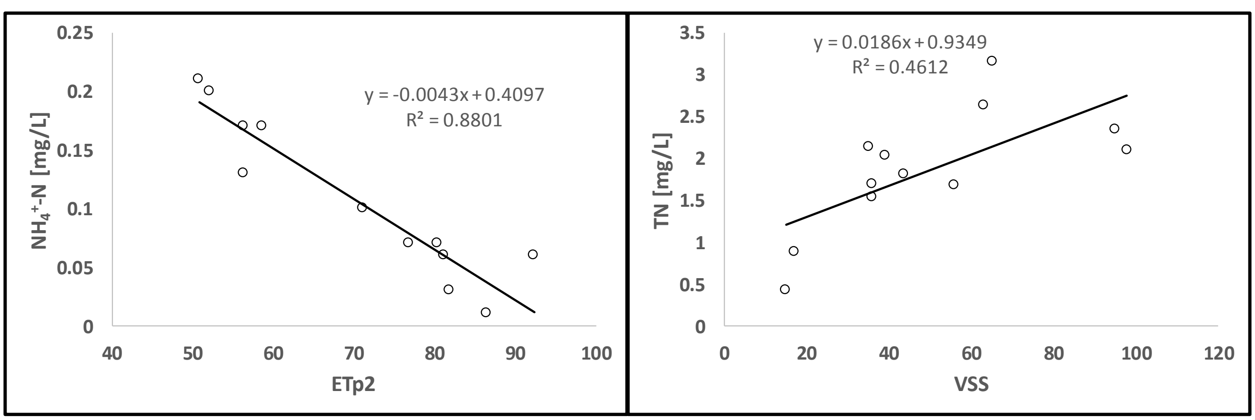

Figure 32. Examples of EMC regression models for TN and NH_4^+-N.
ETp2 = antecedent potential evapotranspiration during the 2 weeks prior to each storm event. VSS = volatile suspended sediments, which is generally the organic portion of TSS.

Relationships between TSS and Turbidity

The dynamic between TSS and turbidity was different on the rising and falling limb of hydrographs in Sessom Creek (Figure 33). For the rising limb, TSS vs turbidity data were more scattered with increasing variability at higher concentrations; likely due to variable antecedent conditions, storm intensities, and percentages of organic detritus during the rising limbs. In contrast, the falling limb relationship had a clear positive linear relationship. Higher levels during the receding limb may be associated with small particles dominating TSS, which are usually inorganic (NVSS) during the receding limb.

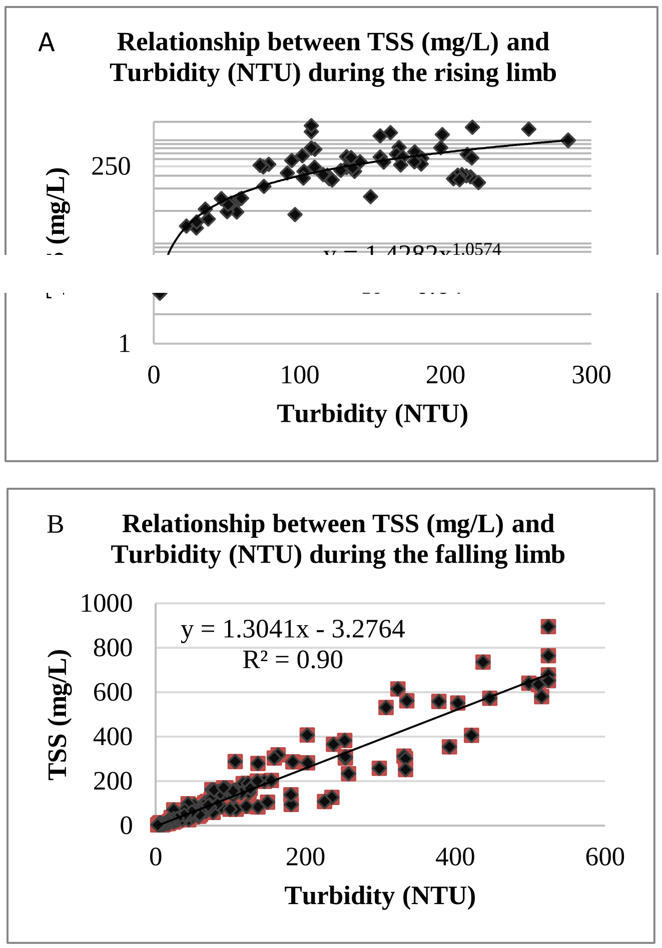

Figure 33 Relationship between TSS and Turbidity during the rising (A) and falling limb (B) of the hydrograph.

Data are from storm events 4 to 12. Events 1-3 are not included because turbidity data were not collected, or due to instrument failure.

Load Analyses

Individual event loads are displayed in Table 11. The largest event loads of SS and nutrients occurred during the largest storms (E1 and E10), although NH_4^+-N loads were highest in E1 and E5 (Figure 7). The largest loads of *E. coli* were during E1, E2, and E6, when concentrations were higher than the maximum detectable limit (>2419 MPN/100mL). In these events, each 100mL represented a diluted sampled with dilution factors between 1/10 to 1/50, which means that actual *E. coli* concentrations during these events were >24,190 to >120,950 MPN/100mL.

All load variables were positively and significantly correlated with each other, except for the relationship between NO_3^--N and NH_4^+-N with TSS and NVSS, which were positive but non-significant after permutations (Table 12). The strongest correlations were observed between TSS and its two constituent parts: VSS and NVSS. Correlations also existed between TSS and TN, TP, and SRP (Pearson > 0.7). Finally, inorganic dissolved nutrients (SRP, NO_3^-N, and NH_4^+-N) had strong correlations with VSS and TN.

Variations in total loads between individual storm events was quite high (Figure 34)Figure 34. Box and whisker outlier plots for total loads of all 12 storm events., but was much lower when the two largest events are removed from the analysis (Figure 35).

Table 11: Summary of accumulated sediment and nutrient loads per storm, and summarized statistics: mean ($\bar{x}$), standard deviation (SD), first quantile (1q), second quantile or median (2q), third quantile (3q)

E	**TSS [kg]**	**VSS [kg]**	**NVSS [kg]**	**TN [kg]**	**TP [kg]**	**NH_4^+-N [kg]**	**NO_3^- -N [kg]**	**SRP [kg]**	***E. coli* (MPN)**
1	36,197.02	6319.83	29877.19	155.73	103.89	11.11	54.49	11.89	>1.52x10^{+15}
2	2357.85	526.74	1831.11	31.95	6.05	2.01	16.85	2.17	>2.67 x10^{+14}
3	171.72	83.02	88.7	4.01	0.42	0.25	1.06	0.01	>4.06 x10^{+13}
4	274.18	101.44	172.74	5.26	0.66	0.44	1.98	0.21	4.26 x10^{+11}
5	2,001.29	529.78	1471.51	24.84	4.63	3.02	7.46	1.41	3.47 x10^{+12}
6	876.2	350.24	525.96	9.81	1.87	0.32	2.81	0.37	>2.88 x10^{+14}
7	177.72	76.44	101.28	3.9	0.62	0.14	1.59	0.21	9.67 x10^{+11}
8	1878.1	404.24	1473.87	17.22	4.15	0.74	6.55	1.06	1.01 x10^{+12}
9	3410.5	481.62	2928.87	14.41	7.41	0.53	3.75	0.64	1.38 x10^{+12}
10	17,166.74	2749.63	14417.1	58.66	23.38	1.65	17.82	2.71	1.53 x10^{+13}
11	547.52	116.27	431.25	4.84	1.28	0.13	1.76	0.18	1.19 x10^{+12}
12	538.86	123.76	415.1	5.09	1.15	0.29	1.93	0.23	4.57 x10^{+13}
$\bar{x}$	5466.48	988.58	4477.89	27.98	12.96	1.72	9.84	1.76	3.39 x10^{+12}
SD	10755.76	1831.57	8928.16	43.32	29.33	3.09	15.21	3.31	5.34 x10^{+12}
1q	472.69	112.56	354.51	5.03	1.03	0.28	1.89	0.21	9.89 x10^{+11}
2q	1377.15	377.24	998.74	12.11	3.01	0.49	3.28	0.51	1.19 x10^{+12}
3q	2621.01	527.50	2105.55	26.62	6.39	1.74	9.81	1.60	2.43 x10^{+12}

"*": MPN (Most Probable Number) was greater than the maximum detectable.

Table 12: Correlation matrix between loads. P-values were obtained by performing permutation to test each correlation.

	TSS	VSS	NVSS	TN	TP	NH_4^+ -N	SRP	NO_3^- -N
TSS	1	0.900***	0.996***	0.755**	0.994***	0.522	0.689*	0.603
VSS	0.900***	1	0.856**	0.906***	0.913***	0.738***	0.840***	0.743***
NVSS	0.996***	0.856**	1	0.705*	0.986***	0.464	0.641*	0.559
TN	0.755**	0.906***	0.705*	1	0.808**	0.860**	0.987***	0.940***
TP	0.994***	0.913***	0.986***	0.808**	1	0.569	0.753*	0.679*
NH_4^+ N	0.522	0.738***	0.464	0.860**	0.569	1	0.829*	0.727*
SRP	0.689*	0.840***	0.641*	0.987***	0.753*	0.829*	1	0.973***
NO_3^- -N	0.603	0.743***	0.559	0.940***	0.679*	0.727*	0.973***	1

* indicates p value <0.05; ** indicates p value <0.01; *** indicates p value <0.001
Absence of asterisk implies p values > 0.05.

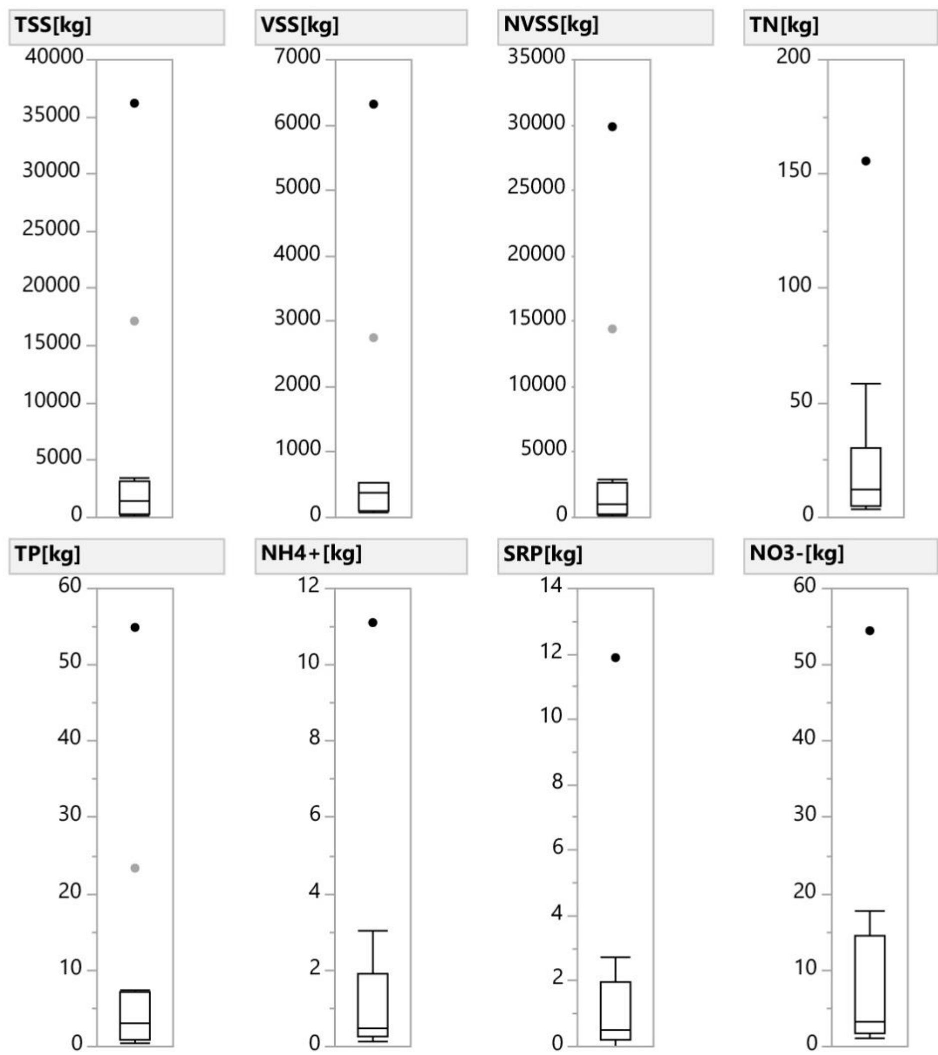

Figure 34. Box and whisker outlier plots for total loads of all 12 storm events.
Note the two largest storm events (#1 and #10) that plot as statistical outliers for most parameters. Mean and quartiles are illustrated.

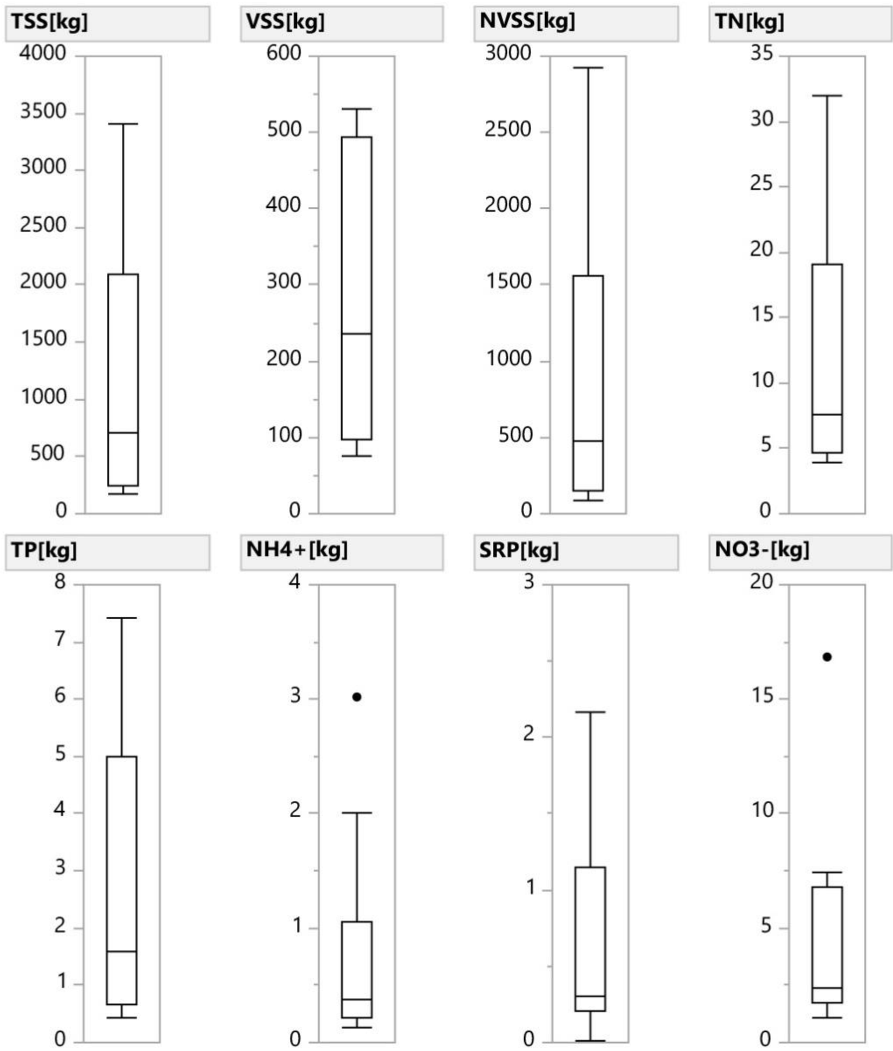

Figure 35. Box and whisker outlier plots for total loads of 10 storm events (not shown: #1 and #10). Mean and quartiles are illustrated.

Load composition

Load composition and magnitudes of TSS, TN and TP (Figure 36 and Figure 37) were variable across the 12 events. Higher percentages of NVSS in TSS (~80%) occurred during higher magnitude storm events (E1, E10, E8 and E9), and conversely, proportions of VSS were higher in smaller events (E3, E4, and E7). In events of high and medium magnitude, VSS was usually between 10-20% of TSS, while in small-magnitude storms, VSS was between 20-45%. Most TP and TN was in particulate, with NH_4^+-N usually comprising less than 10% of TN, and NO_3^--N being the most variable, with the highest % NO_3^--N occurring during E2, E7, and E12. Lastly, SRP varied from ~40% (E2 and E7) to less than 10% (E3 and E9) of TP.

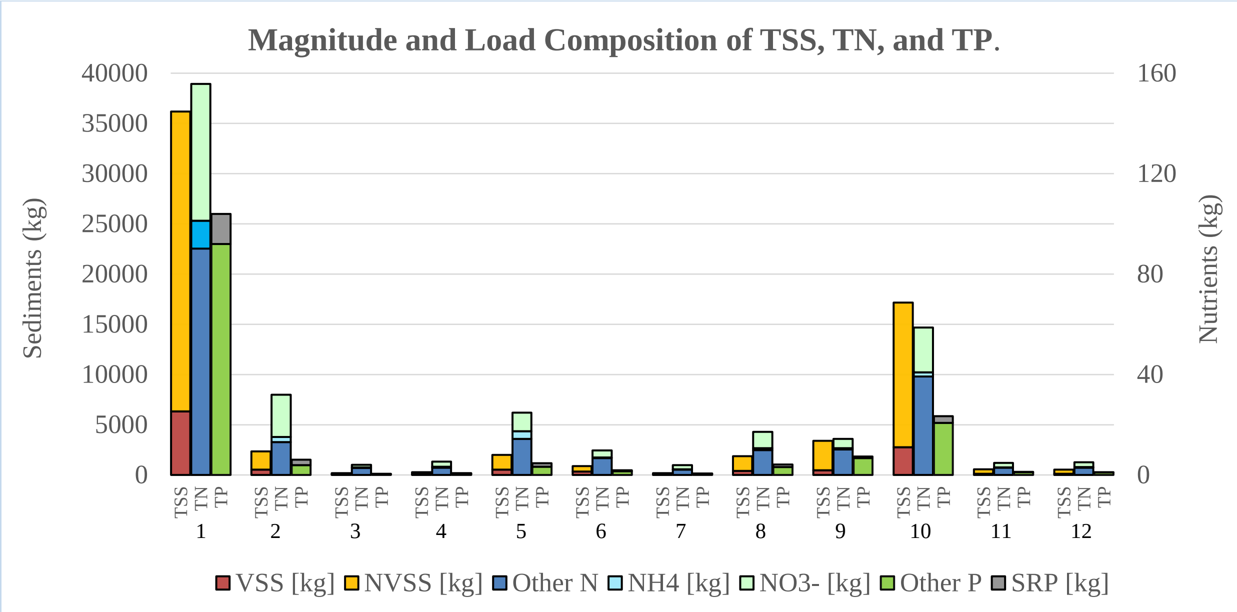

Figure 36. Load compositions during 12 storm events.
"Other N" and "Other P" correspond to undifferentiated forms of TN and TP, most of which are assumed to be particulate organic or inorganic.

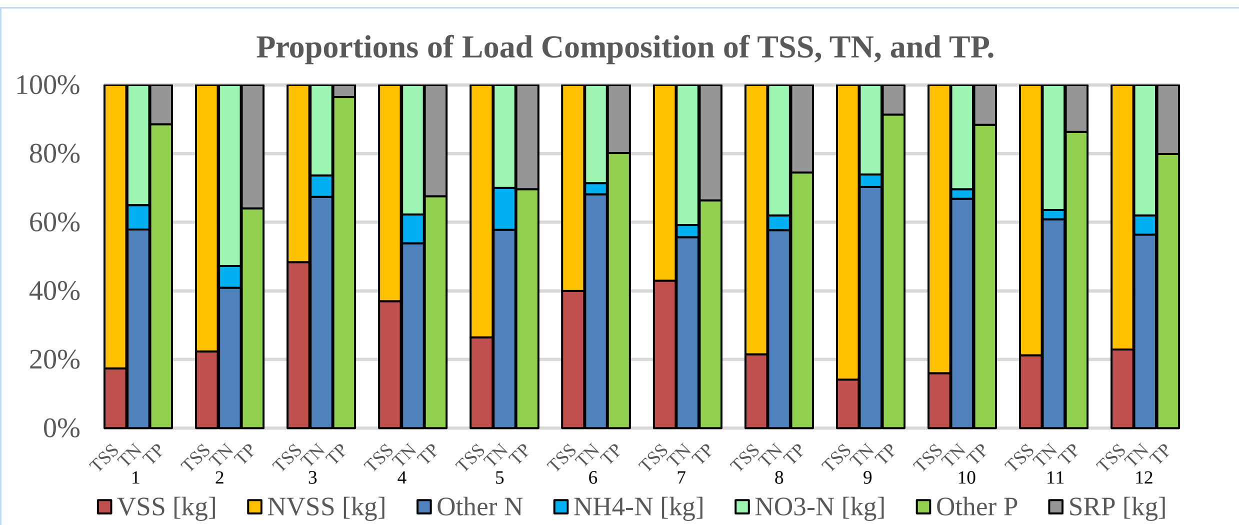

Figure 37. Percentage of the composition of the TSS, TN and TP loads during 12 storm events.
"Other N" and "Other P" correspond to undifferentiated forms of TN and TP, most of which are assumed to be particulate organic or inorganic.

Total NPS loads in the 12 sampled storm events

Individual loads for each NPS constituent, across each of the 12 sampled storm events, were summed to provide a minimum value for what can be expected to be transported into the San Marcos River under current watershed conditions. The summation illustrates that large amounts of NPS constituents are being transported into the river on an annual basis.

As expected, TSS and its constituent parts (VSS and NVSS) constituted the larges proportions by mass Table 13, though loads of dissolved nutrient phases were substantial. Differences by subtraction between the Total nutrient load and the sum of dissolved phases is assumed to represent particulate forms of Nitrogen and Phosphorous.

Table 13. Total NPS loads calculated using measured concentrations in 12 sampled storm events

	TSS [kg]	VSS [kg]	NVSS [kg]	TN [kg]	TP [kg]	NH_4^+-N [kg]	SRP [kg]	NO_3^--N [kg]
Totals	**65,598**	**11,863**	**53,735**	**336**	**107**	**21**	**21**	**118**

Discussion And Conclusions

Measured sediment and phosphorus exports

Suspended sediment exports from the Sessom Creek Watershed to the upper San Marcos River were directly determined for 14 storm runoff events while total phosphorus exports were determined for 12 storm runoff events. Exports were computed by summing the products of concurrently measured stream discharge and constituent concentrations for each event (Table 1). Monitored discharge spanned the range of instrumental measurement capacity, 0.001 to 13.330 m^3/s. Exports occurring during the largest runoff event #1 (27-28 March) are greater than reported as discharge exceeded instrumental measurement capability (Table 1).

Loads calculated using direct measurements are corroborated by values for a 14-month modeled period using LOADEST, though LOADEST was only useful for modeling TSS and TP due to generally poor relationships between discharge and other NPS constituents.

Storm events, NPS Loads and EMCs

The amount of precipitation during storms was highly variable, with the largest events (E1: 132.6 mm, E10: 81.8 mm) causing overbank flow in the lower reaches of the Sessom Creek watershed. Despite the fact that larger rainfall events also produce more total runoff, the amount of runoff in an event is not strongly correlated with the total amount of rain; it is more associated with the intensity of the rain. For example, E4 and E6 had similar total rain (13.5 mm and 15.2 mm respectively), but the runoff generated in each event was different by an order of magnitude (RO for E4 was 2596 m^3, while RO for E6 was 23257 m^3). Differences between these events were that E4 had a Rain Int. of 3.8 mm/hr and a Max RI of 15.24 mm/hr, while E6 had Rain Int. of 26.1 mm/hr and Max RI of 67.1 mm/hr. In addition, E6 was a complex event, where the discharge hydrograph had three peaks. This suggests that, even though the watershed has a high percentage of impervious cover, there is still significant capacity for infiltration, storage, and evapotranspiration during less intense events.

One hundred percent of the measured loads in Sessom Creek were NPS pollutants because there are no point sources in the Sessom Creek Watershed. The magnitude of loads and EMCs in a watershed can be variable (Gellis, 2013), and different studies in small urban watersheds have shown different values for the measured parameters, with data often being skewed for certain variables (Griffin, et al., 1980), which produces challenges for statistical analyses. For example, Appel and Hudack (2001) reported EMCs from 4 storm events of different magnitudes in an urban watershed (35%

urbanized) of North Texas (City of Denton, TX). Their estimations suggested average values of 291 mg/L for TSS, and 950 μg/L for TP in events with less than 25 mm of precipitation, compared with EMCs of this study for TSS (234 ± 189 mg/L) and TP (459 ± 275 μg/L). Comparison of loads or EMCs with other studies can be complicated and lead erroneous conclusions because load calculations are not corrected by the discharge volume, and total loads are likely to be dependent on watershed size. In this sense, when Drewry, et al. (2008) evaluated pollutant loads for sediments and nutrients in a large forested watershed (1810km^2- 85% forest), they found loads of up to 10 times larger during moderate rainfall (~50mm) than those found in this study. This is expected because the watershed area is much larger than Sessom Creek's. On the other hand, Wang, et al. (2011) studied a smaller and more heavily urbanized watershed than the Sessom Creek Watershed (3.6 ha or 0.036 km^2 with >75% impervious cover) and found much higher load values for TSS than values measured in Sessom Creek.

Hysteresis patterns

Sessom Creek sediment hysteresis patterns were evaluated by computing a standardized hysteresis index (HI) and computing summary statistics for all runoff events, runoff events with a single flow peak, and runoff events with multiple flow peaks. As the HI is standardized, the magnitude of each storm runoff event can be ignored allowing comparison across events of different sizes. Within all events, Type 3 and 4 (counterclockwise and figure-8 counterclockwise loops) were slightly more common (53% of events) than Type 1 and 2 (clockwise and figure-8 clockwise loops). This suggests that for slightly more than half of all events, bank erosion, distant sediment sources, dry conditions, and upstream tributaries contributed the bulk of the sediment load. For runoff events with a single flow peak, the same pattern is apparent; 48% of events were Type 3 while only 36% were Type 1. Within multi-peak events, Type 3 and 4 events are even stronger with 54% of the total. The HI also gives an indication of the strength or "fatness" of the hysteresis loop which describes how much the sediment peak leads or lags the discharge peak. For all events, HI was stronger for Type 3 and 4 hysteresis. While slightly more than half of Sessom Creek runoff events are Type 3 or 4, the rest, roughly 35% across all runoff peaks, were of Type 1 and 2 hysteresis which suggests mobilization of in channel sediment sources or that the maximum shear stress on the channel may appear before the peak flow. As much of the watershed is comprised of impervious surfaces, much of this "in channel" source may be comprised of fine organic debris collected within streets, parking lots, and roofs. This was evident in visual color differences observed in collected water quality samples. The first 1-3 samples were often different in color and higher in TSS concentration than later samples. Type 5 hysteresis, a straight line indicating constant erosion and no exhaustion of source, was also observed and ranged from 2 to 16% across all storm peak types.

Regressions and TSS and TP loads based on discharge

Regression models (i.e., rating curves) were developed using USGS LOADEST software to estimate Sessom Creek suspended sediment and total phosphorus concentrations based on measured discharge (Figure 14 and Figure 17). The simplest regression model containing a seasonal time component was selected. After checking residuals for random distribution and equal variance, and verifying that bias statistics were within recommend bounds, the resulting equations were used to generate a time-series of daily estimated loads based on the regressed coefficients for each constituent and daily flow data. AMLE coefficients were used as there were no censored data (i.e., results identical to MLE). Despite their limitations, the regression model rating curves produced by LOADEST provide viable options for estimating suspended sediment and total phosphorus loads based on discharge when continuous time-series water quality data are not available. The estimated sediment load based on discharge for the 14-month monitoring period was 107,520 kg. The estimated total phosphorus load based on discharge for the 14-month monitoring period was 298 kg.

Regression and TSS load based on turbidity

A regression model (i.e., rating curve) was developed using the USGS Turbidity Spreadsheet Tool to estimate Sessom Creek suspended sediment concentration based on measured turbidity (Figure 20). This technique improves suspended sediment load estimation by providing a continuous suspended concentration estimate rather than one interpolated from physical samples. A log-transformed model was selected based on regression statistics. Residuals were examined for normality and equal variance. Continuous turbidity data and streamflow data, calibrated with measured suspended-sediment concentration data, were subsequently used to compute a time series of suspended sediment concentration and suspended-sediment load. The regression model rating curve provides a viable option for estimating suspended sediment concentration based on turbidity when continuous time-series water quality data are not available. The estimated sediment load based on turbidity for the 14-month monitoring period was 65,799 kg.

SWAT conclusions

In general, statistical models are simplistic representations and offer no mechanistic explanation of contaminant sources or transport. They lack spatial detail of sediment sources and sinks within the watershed, do not account for interactions between sources and loss processes, and do not impose mass-balance constraints on entrained constituents. In short, these models may provide a reasonable fit to the observations but provide minimal understanding of the processes affecting constituent transport. In contrast to statistical models, mechanistic water-quality models such as SWAT use a complex mass-balance structure that simulates hydrologic and contaminant transport processes at relatively fine temporal scales.

Because water quality data were not collected daily and a continuous daily record is needed for SWAT model calibration, outputs from the empirical regression models were used to produce continuous time-series to which the SWAT-simulated time-series was compared for calibration.

Challenges in characterizing stormwater and erosion processes in a fast-draining urban catchment were identified. Mainly, a sparse time step simulation can lead to false signals in soil erosion and sediment transport even with reasonable estimation of stormwater discharges. For the Sessom Creek watershed, a 15-minute time step simulation appears to be adequate to capture dynamic hydrographs, soil erosion, and sediment transport processes. Due to the large impervious cover in urban HRUs, upland soil erosion was less significant than channel erosion toward contributing to the sediment yield at the watershed outlet.

Spatial distribution of CSAs appears to be positively correlated with the locations of urban lands and steep land slopes. A detention pond in the Windmill tributary as a stormwater BMP was effective to attenuate peak flow rates for large storms. However, the relatively insignificant contribution of the Windmill tributary to the main channel in terms of flow rate and sediment yield resulted in a marginal reduction in sediment yield at the watershed outlet.

While the detention pond BMP substantially mitigated high peaks, its efficiency on erosion control and sediment delivery was marginal. At the watershed outlet, the model output suggests that only 13.5% reduction of sediment yield is expected with the Windmill detention pond. The sediment reduction rate in the detention pond discharge flow was 18.2%. Further analysis on model output indicates two possible causes for the gap in controlling peak flows and sediment by the detention pond. First, discharge and sediment yield from the Windmill tributary is relatively insignificant to flow in the main Sessom creek at the confluence of the Windmill tributary and Sessom Creek. Therefore, controlling peaks and sediment in the tributary has limited impact to the main channel hydrology. Second, unlike sedimentation ponds or reservoirs, detention time of the pond was short for suspended solids to settle and thus removed before draining to the main creek. The less than 20% reduction of sediment immediately downstream of the detention pond demonstrates that a short detention of a stormwater is ineffective to capture sediment in the flow.

A BMP measure that controls the main channel of the Sessom is recommended for greater reduction of erosion and sediment delivery. It should be noted that the model output may have underestimated water infiltration rate and sediment settling during the detention period of stormwater (in the modeled proposed Windmill tributary detention BMP), though these uncertainties in the model have only limited impact due to the relatively minor effects of these underestimated processes to the total estimated sediment yield at the watershed outlet.

Findings from this study can be used to directly support management actions that seek to reduce NPS pollutant loads from entering the headwaters of the San Marcos River. Actions and efforts include those being implemented by the Edwards Aquifer Conservation Plan (EAHCP). These plans identify stormflow from urban areas as the main water quality concern for the river and recognize that expected urban growth in the region will likely produce water quality impacts in the future (The Meadows Center for Water and the Environment, 2018; Guley, 2012).

Suggestions for management of NPS loads in the Sessom Creek watershed include: 1) reduction of loads from sources (i.e. construction in the watershed, impervious surfaces with no stormwater management, etc.). 2) detention of the initial first flush, and 3) while channel modifications may provide partial reduction in NPS loads and peak flows, efforts could also focus on small-scale retention throughout the watershed, where capture/retention of the first flush can both reduce NPS loads and EMCs, and reduce peak discharges.

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APPENDIX 1 - LOADEST CALIBRATION DATA SETS

```
##############################################
#  LOADEST Calibration File
#  SESSOM CREEK SUSPENDED SEDIMENT (as TSS)
#
#  Monitoring Period
#  - 1 January 2018 to 28 February 2019
##############################################
#CDATE    CTIME   CFLOW   CCONC
##############################################
20180327    2300    26.79    786
20180328    0    21.03    143
20180328    100    15.08    33
20180328    200    186.98    427
20180328    300    332.96    641
20180328    400    45.53    139
20180328    500    21.44    43
20180328    900    22.17    204
20180328    1000    73.65    255
20180328    1100    34.87    98
20180328    1200    13.14    36
20180328    1300    9.33    19
20180328    1400    8.31    10
20180407    0    5.72    245
20180407    100    1.19    17
20180407    200    0.99    6
20180407    300    1.01    2
20180407    400    0.95    1
20180407    500    1.06    1
20180425    1600    7.28    164
20180425    1700    10.11    187
20180425    1800    4.13    65
20180425    1900    1.15    10
20180425    2000    1.12    5
20180425    2100    1.11    2
20180504    900    29.57    293
20180504    1000    44.35    189
20180504    1100    14.85    61
20180504    1200    27.15    58
20180504    1300    23.71    62
20180504    1400    7.80    20
20180525    1200    0.04    2
20180616    1500    22.76    376
20180616    1600    0.69    33
20180616    1700    1.10    13
20180616    1800    1.17    5
20180616    1900    1.11    2
20180619    1000    15.42    66
20180619    1100    21.02    39
20180619    1200    3.89    13
20180619    1300    1.74    8
20180619    1400    1.36    5
20180703    1200    0.04    4
20180704    1400    36.27    318
20180704    1500    38.96    154
20180704    1600    20.87    61
20180704    1700    9.55    44
```

20180704	1800	4.39	26
20180704	1900	1.68	16
20180707	1600	59.68	450
20180707	1700	17.86	426
20180707	1800	4.18	124
20180707	1900	2.06	80
20180707	2000	1.77	50
20180709	1000	41.39	253
20180709	1100	175.05	912
20180709	1200	38.41	176
20180709	1300	12.76	80
20180709	1400	5.27	35
20180709	1500	3.30	27
20180811	1500	0.04	1
20180812	1200	12.27	556
20180812	1300	1.27	32
20180812	1400	2.78	44
20180812	1500	0.54	15
20180907	500	23.92	245
20180907	600	1.72	22
20180907	700	0.61	11
20180907	800	0.26	4
20180907	900	0.50	2
20181207	0	4.61	80
20181207	100	17.84	133
20181207	200	7.80	20
20181207	300	5.36	12
20181207	400	8.69	17
20181207	500	10.00	13
20181207	1700	41.09	58
20181207	1800	37.02	43
20181207	1900	13.10	28
20181207	2000	9.42	17
20181207	2100	10.47	17

```
##################################################################################
#  LOADEST Calibration File
#  SESSOM CREEK TOTAL PHOSPHORUS
#
#  Monitoring Period
#  - 1 January 2018 to 28 February 2019
#
##################################################################################
#CDATE      CTIME   CFLOW   CCONC
##################################################################################
20180328    0       21.03   398
20180328    100     15.08   266
20180328    200     186.98  524
20180328    300     332.96  980
20180328    400     45.53   308
20180328    500     21.44   305
20180328    900     22.17   324
20180328    1000    73.65   588
20180328    1100    34.87   427
20180328    1200    13.14   297
20180328    1300    9.33    221
20180328    1400    8.31    167
20180425    1600    7.28    556
20180425    1700    10.11   424
20180425    1800    4.13    276
20180504    900     29.57   544
20180504    1000    44.35   454
20180504    1100    14.85   277
20180504    1200    27.15   249
20180504    1300    23.71   247
20180504    1400    7.8     225
20180616    1500    22.76   768
20180619    1000    15.42   267
20180619    1100    21.02   167
20180619    1200    3.89    112
20180704    1400    36.27   607
20180704    1500    38.96   441
20180704    1600    20.87   279
20180704    1700    9.55    272
20180704    1800    4.39    205
20180707    1600    59.68   1022
20180707    1800    4.18    519
20180709    1000    41.39   465
20180709    1100    175.05  1480
20180709    1200    38.41   549
20180709    1300    12.76   326
20180709    1400    5.27    240
20180907    500     23.92   536
```

APPENDIX 2 - LOADEST OUTPUTS

LOADEST
A Program to Estimate Constituent Loads
U.S. Geological Survey, Version: MOD48 (March 2013)

Sessom Creek monitoring period, 1 January 2018 to 28 February 2019
Constituent: SESSOM_TSS

Constituent Output File Part Ia: Calibration (Load Regression)

Number of Observations : 73
Number of Uncensored Observations: 73
"center" of Decimal Time : 2018.581
"center" of Ln(Q) : 1.7145
Period of record : 2018-2018

Model Evaluation Criteria Based on AMLE Results

Model #	AIC	SPPC
4	2.547	-97.557

Model # 4 selected

Selected Model:

Ln(Load) = a0 + a1 LnQ + a2 Sin(2 pi dtime) + a3 Cos(2 pi dtime)

where:
Load = constituent load [kg/d]
LnQ = Ln(Q) - center of Ln(Q)
dtime = decimal time - center of decimal time

Model Coefficients

	a0	a1	a2	a3
AMLE	6.1032	1.7312	-0.1978	0.5529
MLE	6.1032	1.7312	-0.1978	0.5529
LAD	5.9351	1.7801	-0.2635	0.7546

AMLE Regression Statistics

R-Squared [%] : 91.57
Residual Variance : 0.7080
Serial Correlation of Residuals: 0.3673
Prob. Plot Corr. Coeff. (PPCC) : 0.9848
Significance Level of PPCC Test: 7.182E-02

Coeff.	Std.Dev.	t-ratio	P Value
a0	0.1200	50.87	6.528E-60
a1	0.0654	26.45	3.675E-40
a2	0.1576	-1.26	1.992E-01
a3	0.1583	3.49	5.656E-04

Correlation Between Explanatory Variables

Explanatory variable corresponding to:

	a1	a2
a2	-0.1104	
a3	-0.3188	-0.0397

Additional Regression Statistics

MLE Residual Variance: 0.7080

Comparison of Observed and Estimated Loads

The summary statistics and bias diagnostics presented below are based on a comparison of observed and estimated loads for all dates/times within the calibration data set. Although this comparison does not directly address errors in load estimation for unsampled dates/times, large discrepancies between observed and estimated loads are indicative of a poor model fit. Additional details and warnings are provided below.

Note: The comparison that follows uses a concentration equal to 1/2 the detection limit when an observation is censored. The summary stats and bias diagnostics are therefore slightly inaccurate for censored data sets.

Summary Stats: Est. and Obs. Loads in [KG/DAY]

	Min.	25th Pct	Med.	75th Pct	90th Pct	95th Pct	99th Pct	Max.
Est.	2.09E-01	2.39E+02	1.42E+03	1.08E+04	3.23E+04	1.18E+05	6.34E+05	6.34E+05
Obs.	3.91E-01	1.80E+02	1.16E+03	9.71E+03	2.72E+04	1.05E+05	5.22E+05	5.22E+05
Est/Obs	0.53	1.33	1.22	1.11	1.19	1.13	1.21	1.21

Est/Obs > 1 indicates overestimation; Est/Obs < 1 indicates underestimation

Bias Diagnostics

Bp [%]	14.281
PLR	1.143
E	0.956

where:

Bp Load Bias in Percent
Positive (negative) values indicate over (under) estimation.
The model should not be used when the + or - bias exceeds 25%

PLR Partial Load Ratio
Sum of estimated loads divided by sum of observed loads.
Values > 1 indicate overestimation; values < 1 indicate underestimation.
PLR = (Bp + 100) / 100

E Nash Sutcliffe Efficiency Index
E ranges from -infinity to 1.0
E = 1; a perfect fit to observed data.
E = 0; model estimates are as accurate as the mean of observed data.

E < 0; the observed mean is a better estimate than the model estimates.

NOTE: Additional information on model calibration is included in the residual output file. LOADEST users should conduct a thorough residuals analysis using the data contained therein (checks for heteroscedasticity and non-normality). Example residual plots are shown in Figures 7, 8, 9, and 17 of the LOADEST documentation (Runkel et al., 2004).

Constituent Output File Part Ib: Calibration (Concentration Regression)

AMLE Regression Statistics

Model # 4 was selected for the load regression (PART Ia) and is used here:

Ln(Conc) = a0 + a1 LnQ + a2 Sin(2 pi dtime) + a3 Cos(2 pi dtime)

where:
Conc = constituent concentration
LnQ = Ln(Q) - center of Ln(Q)
dtime = decimal time - center of decimal time

Concentration Regression Results

R-Squared [%] : 65.72
Residual Variance : 0.7080

Coeff.	Value	Std.Dev.	t-ratio	P Value
a0	3.4940	0.1200	29.12	5.611E-43
a1	0.7312	0.0654	11.17	3.855E-18
a2	-0.1978	0.1576	-1.26	1.992E-01
a3	0.5529	0.1583	3.49	5.656E-04

Comparison of Observed and Estimated Concentrations

The summary statistics and bias diagnostics presented below are based on a comparison of observed and estimated concentrations for all dates/times within the calibration data set. Although this comparison does not directly address errors in concentration estimation for unsampled dates/times, large discrepancies between observed and estimated concentrations are indicative of a poor model fit. Additional details and warnings are provided below.

Note: The comparison that follows uses a concentration equal to 1/2 the detection limit when an observation is censored. The summary stats and bias diagnostics are therefore slightly inaccurate for censored data sets.

Summary Stats: Est. and Obs. Concentrations in MG/L

Min.	25th Pct	Med.	75th Pct	90th Pct	95th Pct	99th Pct	Max.

Est. 2.14E+00 3.52E+01 6.99E+01 1.76E+02 3.33E+02 4.80E+02 1.01E+03 1.01E+03
Obs. 4.00E+00 1.70E+01 4.40E+01 1.70E+02 4.06E+02 5.81E+02 9.12E+02 9.12E+02
Est/Obs 0.53 2.07 1.59 1.03 0.82 0.83 1.11 1.11

Est/Obs > 1 indicates overestimation; Est/Obs < 1 indicates underestimation

Bias Diagnostics

Bp [%] 3.075
PCR 1.031
E 0.572

where:

Bp Concentration Bias in Percent
Positive (negative) values indicate over (under) estimation.
The model should not be used when the + or - bias exceeds 25%

PCR Partial Concentration Ratio
Sum of est. concentrations divided by sum of obs. concentrations.
Values > 1 indicate overestimation; values < 1 indicate underestimation.
PCR = (Bp + 100) / 100

E Nash Sutcliffe Efficiency Index
E ranges from -infinity to 1.0
E = 1; a perfect fit to observed data.
E = 0; model estimates are as accurate as the mean of observed data.
E < 0; the observed mean is a better estimate than the model estimates.

NOTE: Additional information on model calibration is included in the residual output file. LOADEST users should conduct a thorough residuals analysis using the data contained therein (checks for heteroscedasticity and non-normality). Example residual plots are shown in Figures 7, 8, 9, and 17 of the LOADEST documentation (Runkel et al., 2004).

Constituent Output File Part IIa: Estimation (test for extrapolation)
Load Estimates for 20180101-20190228

Streamflow Summary Statistics [cfs]

Data	Mean	Minimum	10th Pct	25th Pct	Median	75th Pct	90th Pct	Maximum
Cal.	24.	0.	1.	2.	10.	24.	43.	333.
Est.	1.	0.	0.	0.	1.	1.	2.	333.

The maximum estimation data set steamflow does not exceed the maximum calibration data set streamflow. No extrapolation is required.

Constituent Output File Part IIb: Estimation (Load Estimates)

Load Estimates for 20180101-20190228

Load Estimates [KG/DAY]

AMLE Load Estimates

	N	Mean Load	95% Conf.Intervals Lower	Upper	Std Error Prediction	Standard Error
Est. Period	10176	261.27	122.37	491.83	95.71	48.56
Jan. 2018	744	21.43	11.43	36.77	6.53	6.46
Feb. 2018	672	10.59	3.34	25.63	5.90	2.47
Mar. 2018	744	1378.	317.	3961.	989.	348.
Apr. 2018	720	42.09	25.30	65.96	10.45	9.75
May 2018	744	117.20	46.45	246.67	52.27	18.70
June 2018	720	45.12	13.78	111.22	25.84	7.40
July 2018	744	906.	208.	2603.	650.	241.
Aug. 2018	744	6.63	1.16	21.71	5.74	1.32
Sep. 2018	720	576.	217.	1251.	271.	164.
Oct. 2018	744	103.88	46.88	200.61	39.89	25.97
Nov. 2018	720	31.02	17.13	51.86	8.94	8.74
Dec. 2018	744	174.03	83.98	320.84	61.29	43.93
Jan. 2019	744	136.25	68.97	242.80	44.90	33.03
Feb. 2019	672	53.77	30.47	88.17	14.85	14.69

MLE Load Estimates

	N	Mean Load	Standard Error
Est. Period	10176	261.29	48.43
Jan. 2018	744	21.43	6.45
Feb. 2018	672	10.59	2.47
Mar. 2018	744	1378.	348.
Apr. 2018	720	42.09	9.74
May 2018	744	117.22	18.63
June 2018	720	45.13	7.37
July 2018	744	906.14	240.24
Aug. 2018	744	6.63	1.32
Sep. 2018	720	575.72	163.58
Oct. 2018	744	103.89	25.93
Nov. 2018	720	31.02	8.72
Dec. 2018	744	174.04	43.86
Jan. 2019	744	136.26	32.98
Feb. 2019	672	53.78	14.67

LAD Load Estimates

N	Mean Load	Standard Error

Est. Period	10176	303.97	63.74
Jan. 2018	744	16.01	5.93
Feb. 2018	672	8.80	2.84
Mar. 2018	744	1524.	412.
Apr. 2018	720	38.98	13.28
May 2018	744	129.43	27.06
June 2018	720	55.65	10.90
July 2018	744	1270.	384.
Aug. 2018	744	7.91	2.15
Sep. 2018	720	707.26	298.57
Oct. 2018	744	100.89	36.10
Nov. 2018	720	25.67	8.18
Dec. 2018	744	151.41	52.54
Jan. 2019	744	111.47	35.46
Feb. 2019	672	42.06	15.50

Summary Statistics - Estimated Loads [KG/DAY]

	Min.	25th Pct	Med.	75th Pct	90th Pct	95th Pct	99th Pct	Max.
AMLE	0.	0.	23.	38.	56.	72.	1032.	634401.
MLE	0.	0.	23.	38.	56.	72.	1033.	634452.
LAD	0.	0.	19.	34.	44.	66.	940.	720424.

Summary Statistics - Estimated Concentrations [MG/L]

	Min.	25th Pct	Med.	75th Pct	90th Pct	95th Pct	99th Pct	Max.
AMLE	0.60	1.84	9.10	12.20	15.24	18.55	53.58	1009.53
MLE	0.60	1.84	9.11	12.20	15.25	18.55	53.58	1009.61
LAD	0.41	1.76	6.99	10.15	14.59	17.58	51.11	1465.21

LOADEST
A Program to Estimate Constituent Loads
U.S. Geological Survey, Version: MOD48 (March 2013)

Sessom Creek monitoring period, 1 January 2018 to 28 February 2019

Constituent: echo_SESSOM_TP

Constituent Output File Part Ia: Calibration (Load Regression)

Number of Observations : 38
Number of Uncensored Observations: 38
"center" of Decimal Time : 2018.397
"center" of Ln(Q) : 3.3150
Period of record : 2018-2018

Model Evaluation Criteria Based on AMLE Results

Model #	AIC	SPPC
4	1.051	-23.237

Model # 4 selected

Selected Model:

Ln(Load) = a0 + a1 LnQ + a2 Sin(2 pi dtime) + a3 Cos(2 pi dtime)

where:
Load = constituent load [kg/d]
LnQ = Ln(Q) - center of Ln(Q)
dtime = decimal time - center of decimal time

Model Coefficients

	a0	a1	a2	a3
AMLE	3.3994	1.3610	0.1857	-0.0966
MLE	3.3994	1.3610	0.1857	-0.0966
LAD	3.4265	1.4084	0.1773	-0.1978

AMLE Regression Statistics

R-Squared [%] : 93.59
Residual Variance : 0.1507
Serial Correlation of Residuals: 0.2798
Prob. Plot Corr. Coeff. (PPCC) : 0.9838
Significance Level of PPCC Test: 2.860E-01

Coeff. Std.Dev. t-ratio P Value

a0	0.2192	15.51	5.167E-19
a1	0.0628	21.66	4.586E-24
a2	0.0964	1.93	4.726E-02
a3	0.2983	-0.32	7.323E-01

Correlation Between Explanatory Variables

Explanatory variable corresponding to:

	a1	a2
a2	-0.1299	
a3	-0.2328	0.1442

Additional Regression Statistics

MLE Residual Variance: 0.1507

Comparison of Observed and Estimated Loads

The summary statistics and bias diagnostics presented below are based on a comparison of observed and estimated loads for all dates/times within the calibration data set. Although this comparison does not directly address errors in load estimation for unsampled dates/times, large discrepancies between observed and estimated loads are indicative of a poor model fit. Additional details and warnings are provided below.

Note: The comparison that follows uses a concentration equal to 1/2 the detection limit when an observation is censored. The summary stats and bias diagnostics are therefore slightly inaccurate for censored data sets.

Summary Stats: Est. and Obs. Loads in [G/DAY]

	Min.	25th Pct	Med.	75th Pct	90th Pct	95th Pct	99th Pct	Max.
Est.	2.03E+03	6.66E+03	2.07E+04	5.19E+04	1.25E+05	4.36E+05	7.66E+05	7.66E+05
Obs.	1.07E+03	8.03E+03	1.52E+04	4.38E+04	1.58E+05	6.42E+05	7.98E+05	7.98E+05
Est/Obs	1.91	0.83	1.37	1.18	0.79	0.68	0.96	0.96

Est/Obs > 1 indicates overestimation; Est/Obs < 1 indicates underestimation

Bias Diagnostics

Bp [%]	-5.258
PLR	0.947
E	0.934

where:

Bp Load Bias in Percent
Positive (negative) values indicate over (under) estimation.
The model should not be used when the + or - bias exceeds 25%

PLR Partial Load Ratio
Sum of estimated loads divided by sum of observed loads.
Values > 1 indicate overestimation; values < 1 indicate underestimation.
PLR = (Bp + 100) / 100

E Nash Sutcliffe Efficiency Index
E ranges from -infinity to 1.0
E = 1; a perfect fit to observed data.
E = 0; model estimates are as accurate as the mean of observed data.
E < 0; the observed mean is a better estimate than the model estimates.

NOTE: Additional information on model calibration is included in the residual output file. LOADEST users should conduct a thorough residuals analysis using the data contained therein (checks for heteroscedasticity and non-normality). Example residual plots are shown in Figures 7, 8, 9, and 17 of the LOADEST documentation (Runkel et al., 2004).

Constituent Output File Part Ib: Calibration (Concentration Regression)

AMLE Regression Statistics

Model # 4 was selected for the load regression (PART Ia) and is used here:

Ln(Conc) = a0 + a1 LnQ + a2 Sin(2 pi dtime) + a3 Cos(2 pi dtime)

where:
Conc = constituent concentration
LnQ = Ln(Q) - center of Ln(Q)
dtime = decimal time - center of decimal time

Concentration Regression Results

R-Squared [%] : 52.04
Residual Variance : 0.1507

Coeff.	Value	Std.Dev.	t-ratio	P Value
a0	6.0975	0.2192	27.82	5.230E-28
a1	0.3610	0.0628	5.74	3.841E-07
a2	0.1857	0.0964	1.93	4.726E-02
a3	-0.0966	0.2983	-0.32	7.323E-01

Comparison of Observed and Estimated Concentrations

The summary statistics and bias diagnostics presented below are based on a comparison of observed and estimated concentrations for all dates/times within the calibration data set. Although this comparison does not directly address errors in concentration estimation

for unsampled dates/times, large discrepancies between observed and estimated concentrations are indicative of a poor model fit. Additional details and warnings are provided below.

Note: The comparison that follows uses a concentration equal to 1/2 the detection limit when an observation is censored. The summary stats and bias diagnostics are therefore slightly inaccurate for censored data sets.

Summary Stats: Est. and Obs. Concentrations in UG/L

	Min.	25th Pct	Med.	75th Pct	90th Pct	95th Pct	99th Pct	Max.
Est.	2.01E+02	2.79E+02	3.85E+02	5.36E+02	6.74E+02	9.43E+02	9.77E+02	9.77E+02
Obs.	1.12E+02	2.62E+02	3.25E+02	5.38E+02	7.89E+02	1.04E+03	1.48E+03	1.48E+03
Est/Obs	1.79	1.06	1.18	1.00	0.85	0.90	0.66	0.66

Est/Obs > 1 indicates overestimation; Est/Obs < 1 indicates underestimation

Bias Diagnostics

Bp [%]	-0.592
PCR	0.994
E	0.621

where:

Bp Concentration Bias in Percent
Positive (negative) values indicate over (under) estimation.
The model should not be used when the + or - bias exceeds 25%

PCR Partial Concentration Ratio
Sum of est. concentrations divided by sum of obs. concentrations.
Values > 1 indicate overestimation; values < 1 indicate underestimation.
PCR = (Bp + 100) / 100

E Nash Sutcliffe Efficiency Index
E ranges from -infinity to 1.0
E = 1; a perfect fit to observed data.
E = 0; model estimates are as accurate as the mean of observed data.
E < 0; the observed mean is a better estimate than the model estimates.

NOTE: Additional information on model calibration is included in the residual output file. LOADEST users should conduct a thorough residuals analysis using the data contained therein (checks for heteroscedasticity and non-normality). Example residual plots are shown in Figures 7, 8, 9, and 17 of the LOADEST documentation (Runkel et al., 2004).

Constituent Output File Part IIa: Estimation (test for extrapolation)

Load Estimates for 20180101-20190228

Streamflow Summary Statistics [cfs]

Data	Mean	Minimum	10th Pct	25th Pct	Median	75th Pct	90th Pct	Maximum
Cal.	39.	4.	4.	9.	21.	39.	84.	333.
Est.	1.	0.	0.	0.	1.	1.	2.	333.

The maximum estimation data set streamflow does not exceed the maximum calibration data set streamflow. No extrapolation is required.

Constituent Output File Part IIb: Estimation (Load Estimates)
Load Estimates for 20180101-20190228

Load Estimates [G/DAY]

AMLE Load Estimates

	N	Mean Load	95% Conf.Intervals Lower	95% Conf.Intervals Upper	Std Error Prediction	Standard Error
Est. Period	10176	732.	393.	1251.	221.	217.
Jan. 2018	744	332.16	104.04	807.03	186.14	186.07
Feb. 2018	672	96.61	45.30	181.70	35.33	33.85
Mar. 2018	744	2153.	1265.	3435.	558.	312.
Apr. 2018	720	329.80	216.12	482.60	68.31	67.96
May 2018	744	366.30	264.38	494.70	58.92	44.41
June 2018	720	109.78	71.48	161.46	23.07	11.26
July 2018	744	1180.	723.	1822.	282.	147.
Aug. 2018	744	27.56	13.00	51.64	10.01	7.36
Sep. 2018	720	1475.	664.	2853.	568.	542.
Oct. 2018	744	718.	201.	1856.	442.	439.
Nov. 2018	720	418.	92.	1226.	309.	309.
Dec. 2018	744	1182.	323.	3105.	744.	740.
Jan. 2019	744	1149.	390.	2661.	598.	596.
Feb. 2019	672	625.	288.	1191.	234.	234.

MLE Load Estimates

	N	Mean Load	Standard Error
Est. Period	10176	732.42	217.29
Jan. 2018	744	332.16	186.06

Feb. 2018	672	96.61	33.85
Mar. 2018	744	2153.	311.
Apr. 2018	720	329.81	67.94
May 2018	744	366.30	44.37
June 2018	720	109.78	11.24
July 2018	744	1180.	146.
Aug. 2018	744	27.56	7.36
Sep. 2018	720	1475.	542.
Oct. 2018	744	717.78	439.43
Nov. 2018	720	418.36	308.70
Dec. 2018	744	1182.	740.
Jan. 2019	744	1149.	596.
Feb. 2019	672	625.08	234.14

LAD Load Estimates

	N	Mean Load	Standard Error
Est. Period	10176	837.53	142.23
Jan. 2018	744	372.03	132.65
Feb. 2018	672	99.77	25.93
Mar. 2018	744	2438.	267.
Apr. 2018	720	293.88	42.48
May 2018	744	343.09	32.33
June 2018	720	104.24	13.58
July 2018	744	1244.	189.
Aug. 2018	744	27.27	3.66
Sep. 2018	720	1747.	289.
Oct. 2018	744	877.42	256.25
Nov. 2018	720	510.81	186.61
Dec. 2018	744	1532.	533.
Jan. 2019	744	1375.	457.
Feb. 2019	672	649.08	181.06

Summary Statistics - Estimated Loads [G/DAY]

	Min.	25th Pct	Med.	75th Pct	90th Pct	95th Pct	99th Pct	Max.
AMLE	3.	4.	263.	451.	671.	772.	6248.	766273.
MLE	3.	4.	263.	451.	671.	772.	6248.	766281.
LAD	2.	3.	264.	528.	737.	876.	7275.	910371.

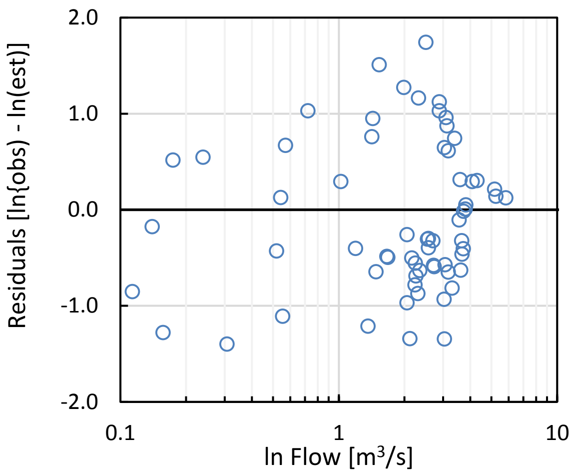
Summary Statistics - Estimated Concentrations [UG/L]

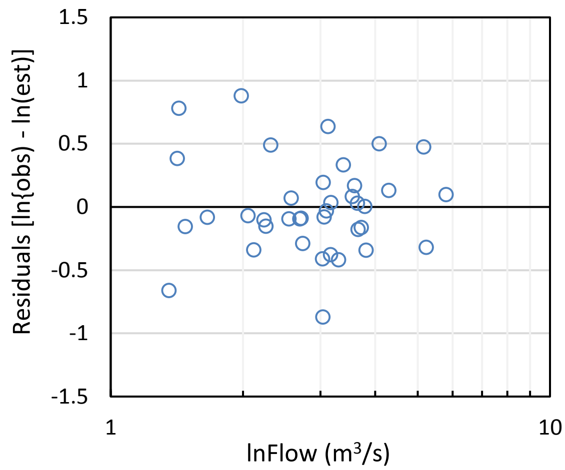
	Min.	25th Pct	Med.	75th Pct	90th Pct	95th Pct	99th Pct	Max.
AMLE	32.	45.	121.	143.	154.	169.	295.	977.
MLE	32.	45.	121.	143.	154.	169.	295.	977.
LAD	27.	38.	111.	162.	180.	192.	359.	1118.

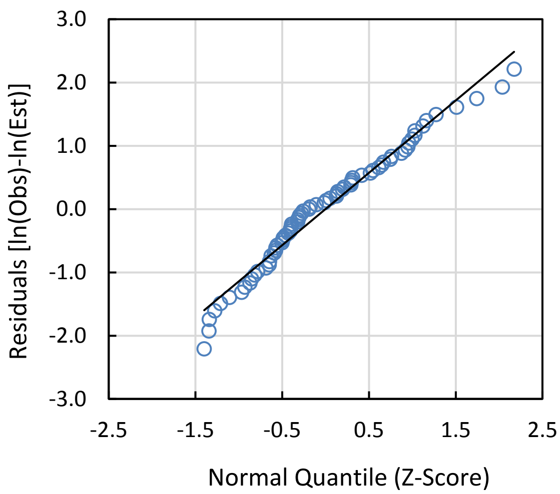
APPENDIX 3 - LOADEST REGRESSION RESIDUAL PLOTS

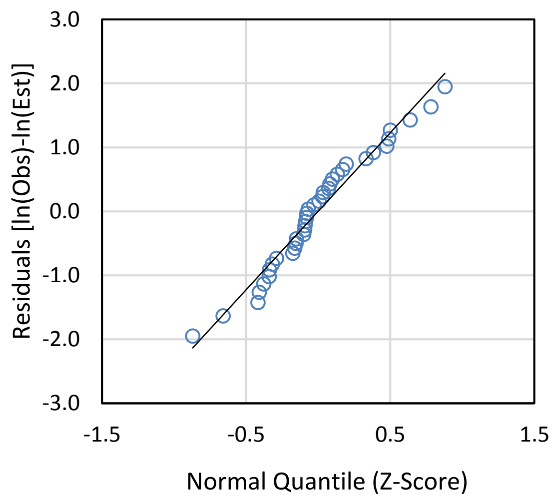
Suspended Sediment

Total Phosphorus









APPENDIX 4 - TURBIDITY CALIBRATION SET

Turbidity calibration data set for Sessom Creek, April to December 2018.

Date	Time	Turbidity [NTU]	Flow [ft^3/s]	TSS [mg/L]
4/25/2018	16:32	217	10.21	180
4/25/2018	16:35	214	10.01	185
4/25/2018	16:38	212	9.88	192
4/25/2018	16:41	208	9.71	173
4/25/2018	16:44	205	9.8	169
4/25/2018	16:47	210	9.89	164
4/25/2018	16:52	223	9.8	149
4/25/2018	16:57	235	9.37	126
4/25/2018	17:02	225	8.72	107
4/25/2018	17:07	190	7.93	94
4/25/2018	17:12	146	7.11	83
4/25/2018	17:17	108	6.97	73
4/25/2018	17:27	97	6.02	55
4/25/2018	17:37	141	11.73	96
4/25/2018	17:47	204	15.03	443
4/25/2018	17:57	132	13.3	148
4/25/2018	18:07	90	10.02	83
4/25/2018	18:17	69	5.83	62
4/25/2018	18:47	30	1.27	25
4/25/2018	19:17	12	1.11	10
4/25/2018	19:47	6	1.22	11
4/25/2018	20:17	5	1.12	7
4/25/2018	20:47	6	1.12	4
4/25/2018	21:17	6	1.12	2
5/4/2018	09:31	104	20.08	420
5/4/2018	09:34	103	30.98	521
5/4/2018	09:37	102	41.87	363
5/4/2018	09:40	101	52.77	212
5/4/2018	09:43	101	58.23	298
5/4/2018	09:46	105	63.69	263
5/4/2018	09:51	131	71.58	244
5/4/2018	09:56	151	74.06	287
5/4/2018	10:01	176	77.16	279
5/4/2018	10:06	179	62.71	336
5/4/2018	10:11	182	48.26	285
5/4/2018	10:16	185	47.9	188
5/4/2018	10:26	143	45.57	142
5/4/2018	10:36	115	41.3	129
5/4/2018	10:46	96	34.98	102

5/4/2018	10:56	81	29.06	91
5/4/2018	11:06	70	18.73	72
5/4/2018	11:16	63	11.68	48
5/4/2018	11:46	91	15.55	59
5/4/2018	12:16	81	27.51	60
5/4/2018	12:46	68	26.07	56
5/4/2018	13:16	76	29.23	75
5/4/2018	13:46	49	16.79	38
5/4/2018	14:16	43	9.16	20
6/16/2018	15:01	275	33.76	983
6/16/2018	15:04	327	46.83	1156
6/16/2018	15:07	335	46.9	360
6/16/2018	15:10	308	37.2	320
6/16/2018	15:13	279	35.8	333
6/16/2018	15:16	249	47.34	240
6/16/2018	15:21	142	44.32	201
6/16/2018	15:26	124	49.66	147
6/16/2018	15:31	133	12.56	170
6/16/2018	15:36	117	9.86	108
6/16/2018	15:41	98	3.94	72
6/16/2018	15:46	79	3.56	62
6/16/2018	15:56	62	1.65	44
6/16/2018	16:06	49	1.11	32
6/16/2018	16:16	35	0.82	33
6/16/2018	17:46	9	1.17	13
6/16/2018	18:16	14	1.18	6
6/16/2018	18:46	15	1.16	4
6/16/2018	19:16	13	1.15	2
6/16/2018	19:46	12	1.09	3
6/19/2018	10:13	95	13.43	79
6/19/2018	10:16	112	14.35	89
6/19/2018	10:19	88	20.02	92
6/19/2018	10:22	75	26.39	76
6/19/2018	10:25	68	20.6	98
6/19/2018	10:28	62	16.04	68
6/19/2018	10:33	52	12.61	43
6/19/2018	10:38	46	12.86	36
6/19/2018	10:43	47	18.12	44
6/19/2018	10:48	45	15.64	38
6/19/2018	10:53	46	14.92	38
6/19/2018	10:58	66	30.89	90
6/19/2018	11:08	53	31.58	65
6/19/2018	11:18	37	13.14	29

6/19/2018	11:28	34	12.45	22
6/19/2018	12:58	33	2.27	13
6/19/2018	13:28	29	1.64	9
6/19/2018	13:58	24	1.51	8
6/19/2018	14:28	21	1.35	6
6/19/2018	14:58	18	1.32	5
7/4/2018	14:07	11	0.03	4
7/4/2018	14:31	162	38.61	882
7/4/2018	14:34	264	75.67	437
7/4/2018	14:37	284	90.39	487
7/4/2018	14:40	216	92	255
7/4/2018	14:43	193	70.76	190
7/4/2018	14:46	171	72.07	152
7/4/2018	14:51	171	70.77	153
7/4/2018	14:56	276	77.89	318
7/4/2018	15:01	317	78.47	281
7/4/2018	15:06	244	46.02	198
7/4/2018	15:11	198	44.25	159
7/4/2018	15:16	142	41.89	146
7/4/2018	15:26	141	33.91	147
7/4/2018	15:36	125	37.84	95
7/4/2018	15:46	111	30.48	81
7/4/2018	15:56	117	36.74	120
7/4/2018	16:06	97	30.28	65
7/4/2018	16:16	93	28.35	56
7/4/2018	16:46	97	13.59	50
7/4/2018	17:16	86	10.32	42
7/4/2018	17:46	82	7.96	38
7/4/2018	18:16	65	5.76	29
7/4/2018	18:46	51	2.77	20
7/4/2018	19:16	34	1.81	16
7/7/2018	16:10	112	11.95	346
7/7/2018	16:13	123	65.01	259
7/7/2018	16:16	99	71.92	218
7/7/2018	16:19	124	75.78	283
7/7/2018	16:22	139	90.42	335
7/7/2018	16:25	138	118.82	303
7/7/2018	16:30	182	74.77	365
7/7/2018	16:35	292	74.02	557
7/7/2018	16:40	314	70.12	550
7/7/2018	16:45	347	77.37	640
7/7/2018	16:50	419	73.14	634
7/7/2018	16:55	448	46.69	580

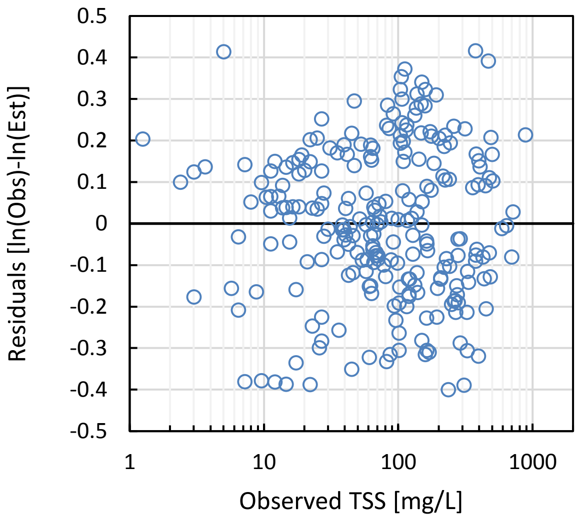
7/7/2018	17:05	391	41	572
7/7/2018	17:15	331	20.77	405
7/7/2018	17:25	303	13.61	354
7/7/2018	17:35	275	11.16	306
7/7/2018	17:45	246	9.59	251
7/7/2018	17:55	216	7.95	233
7/7/2018	18:25	164	3.9	137
7/7/2018	18:55	124	2.83	105
7/7/2018	19:25	110	2.04	87
7/7/2018	19:55	87	1.85	72
7/7/2018	20:25	73	1.76	58
7/7/2018	20:55	55	1.68	42
7/9/2018	10:18	161	35.02	391
7/9/2018	10:21	131	75.68	287
7/9/2018	10:24	167	77.26	322
7/9/2018	10:27	223	72.16	266
7/9/2018	10:30	150	79.28	211
7/9/2018	10:33	101	78.12	186
7/9/2018	10:38	99	40.17	169
7/9/2018	10:43	99	31.97	162
7/9/2018	10:48	100	16.79	237
7/9/2018	10:53	107	38.84	192
7/9/2018	10:58	132	80	327
7/9/2018	11:23	540	303.58	1446
7/9/2018	11:33	457	120.52	763
7/9/2018	11:43	331	78.49	614
7/9/2018	11:53	192	70.96	306
7/9/2018	12:03	127	44.47	203
7/9/2018	12:33	105	38.95	166
7/9/2018	13:03	53	24.09	93
7/9/2018	13:33	42	11.07	52
7/9/2018	14:03	45	8.4	37
7/9/2018	14:33	34	4.78	30
7/9/2018	15:03	32	2.93	27
8/12/2018	12:08	219	42.42	912
8/12/2018	12:11	344	34.08	734
8/12/2018	12:14	286	31.41	561
8/12/2018	12:17	238	17.04	531
8/12/2018	12:20	195	14.14	382
8/12/2018	12:23	156	13.27	257
8/12/2018	12:28	108	9.24	200
8/12/2018	12:33	82	4.62	141
8/12/2018	12:38	66	2.75	96

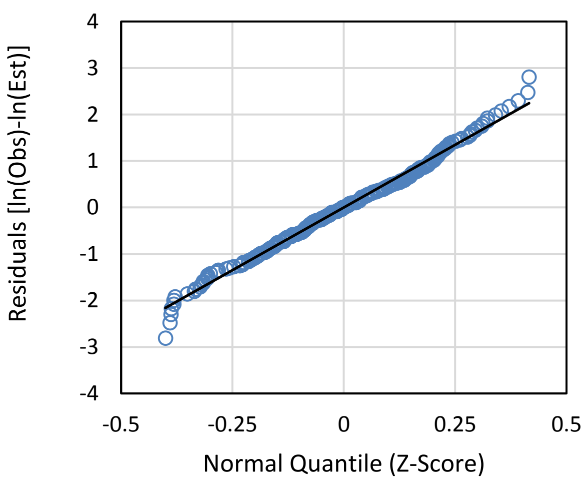
8/12/2018	12:43	58	1.82	82
8/12/2018	12:48	51	1.51	74
8/12/2018	12:53	46	1.33	61
8/12/2018	13:03	34	1.05	48
8/12/2018	13:13	32	0.93	40
8/12/2018	13:23	29	1.02	35
8/12/2018	13:33	26	1.11	28
8/12/2018	13:43	25	1.34	26
8/12/2018	13:53	25	1.73	24
8/12/2018	14:23	49	4.02	49
8/12/2018	14:53	27	1.13	27
8/12/2018	15:23	22	0.56	16
8/12/2018	15:53	15	0.28	12
9/7/2018	05:06	338	27.94	789
9/7/2018	05:09	277	37.65	559
9/7/2018	05:12	148	39.57	287
9/7/2018	05:15	120	44.92	241
9/7/2018	05:18	103	47.07	172
9/7/2018	05:21	103	50.96	154
9/7/2018	05:26	85	37.04	145
9/7/2018	05:31	83	30.17	160
9/7/2018	05:36	90	14.04	169
9/7/2018	05:41	67	12	90
9/7/2018	05:46	48	9.28	61
9/7/2018	05:51	38	7.25	47
9/7/2018	06:01	29	3.56	31
9/7/2018	06:11	23	1.83	23
9/7/2018	06:21	20	1.77	17
9/7/2018	06:31	18	1.72	17
9/7/2018	06:41	20	1.47	15
9/7/2018	06:51	19	1.17	15
9/7/2018	07:21	17	0.65	12
9/7/2018	07:51	13	0.48	9
9/7/2018	08:21	10	0.4	4
9/7/2018	08:51	7	0.08	5
9/7/2018	09:21	5	0.15	3
9/7/2018	09:51	3	0.84	2
12/7/2018	00:57	111	7.64	80
12/7/2018	01:00	142	7.97	81
12/7/2018	01:03	139	7.64	77
12/7/2018	01:06	132	7.32	78
12/7/2018	01:09	120	6.99	94
12/7/2018	01:12	109	7.86	119

12/7/2018	01:17	102	10.29	129
12/7/2018	01:22	179	15.23	172
12/7/2018	01:27	285	23.91	189
12/7/2018	01:32	245	30.92	161
12/7/2018	01:37	162	35.4	115
12/7/2018	01:42	111	32.85	137
12/7/2018	01:52	74	11.67	80
12/7/2018	02:02	34	10.35	36
12/7/2018	02:12	23	8.28	18
12/7/2018	02:22	17	7.48	15
12/7/2018	02:32	17	5.72	10
12/7/2018	02:42	16	5.53	12
12/7/2018	03:12	22	7.59	14
12/7/2018	03:42	11	3.51	6
12/7/2018	04:12	34	11.47	14
12/7/2018	04:42	21	8.19	20
12/7/2018	05:12	24	6.62	12
12/7/2018	05:42	30	11.41	13
12/7/2018	17:01	73	38.29	59
12/7/2018	17:04	72	35.38	69
12/7/2018	17:07	71	32.47	58
12/7/2018	17:10	69	29.57	53
12/7/2018	17:13	68	27.69	57
12/7/2018	17:16	67	25.81	43
12/7/2018	17:19	65	23.93	43
12/7/2018	17:21	66	25.52	44
12/7/2018	17:23	68	29.96	65
12/7/2018	17:26	69	36.62	72
12/7/2018	17:31	71	45.81	57
12/7/2018	17:46	66	51.91	58
12/7/2018	17:56	62	53.41	57
12/7/2018	18:06	59	48.13	44
12/7/2018	18:16	57	49.92	53
12/7/2018	18:26	52	44.82	35
12/7/2018	18:36	50	33.27	43
12/7/2018	18:46	47	23.36	38
12/7/2018	19:16	42	13.45	30
12/7/2018	19:46	35	12.45	26
12/7/2018	20:16	28	9.77	17
12/7/2018	20:45	21	9.03	16
12/7/2018	21:16	25	11.61	20
12/7/2018	21:46	17	10.07	13

APPENDIX 5 - TURBIDITY REGRESSION RESIDUAL PLOTS

Suspended sediment (as TSS) estimated by turbidity





APPENDIX 6 – TABLES OF MEASURED PARAMETERS FOR 12 STORM EVENTS

Summary of water quality variables measured during storm event 1.

Time [CST] [MM/DD/YYYY HH:MM:SS]	Sample	Discharge [m^3/s]	TSS [mg/L]	VSS [mg/L]	NVSS [mg/L]	TN [µg/L]	TP [µg/L]	NH_4^+-N [µg/L]	SRP [µg/L]	NO_3^--N [µg/L]	*E. coli* (MPN/ 100mL)
3/27/2018 23:26	1	1.22	1797.69	402.68	1395.02	9652.92	2644.84	172.56	98.84	762.88	>24192
3/27/2018 23:26	1LD	1.22									>24192
3/27/2018 23:29	2	1.83	1369.87	381.18	988.69	6877.37	2059.59	149.83	43.82	857.62	>24192
3/27/2018 23:32	3	2.01	1590.46	364.33	1226.13	5382.24	1929.62	144.84	80.22	621.64	>24192
3/27/2018 23:35	4	1.99	660.59	161.68	498.91	4962.70	1464.46	168.67	161.99	425.10	24191.7
3/27/2018 23:38	5	1.97	484.53	135.45	349.09	3960.00	883.94	201.69	192.29	472.49	19862.8
3/27/2018 23:41	6	1.80	249.77	74.59	175.19	3753.50	737.12	188.60	170.11	462.08	15530.7
3/27/2018 23:44	7	1.35	191.80	80.97	110.83	3669.35	609.00	171.16	186.03	550.02	14136
3/27/2018 23:49	8	0.59	227.35	81.17	146.18	3593.75	569.31	151.70	147.26	823.48	>24192
3/27/2018 23:54	9	0.41	123.33	49.99	73.34	3909.66	563.35	131.61	133.54	658.51	>24192
3/27/2018 23:59	10	0.31	116.67	46.40	70.27	3908.24	516.67	103.11	104.09	949.35	>24192
3/27/2018 23:59	10LD	0.31									>24192
3/28/2018 0:04	11	0.29	96.41	49.29	47.12	3737.88	475.75	65.73	106.46	906.63	>24192
3/28/2018 0:09	12	0.28	99.10	44.39	54.72	3580.89	520.58	78.19	101.38	1036.96	>24192
3/28/2018 0:14	13	0.59	154.47	52.07	102.40	3928.05	595.84	124.44	59.56	1161.05	3724
3/28/2018 0:24	14	0.30	169.92	59.59	110.33	2932.61	383.83	119.46	93.42	537.77	19862.8
3/28/2018 0:34	15	0.93	116.59	53.62	62.97	2657.97	412.00	109.34	99.18	521.95	24191.7
3/28/2018 0:43	16FD	0.30	59.70	31.40	28.30	2249.23	311.44	104.82	103.24	535.71	24191.7
3/28/2018 0:43	16FD-SSC	0.30	255.18	50.53	204.65						
3/28/2018 0:44	16	0.30	61.15	31.69	29.46	2164.44	218.90	61.37	66.16	542.61	>24192
3/28/2018 0:54	17	0.29	44.98	25.21	19.78	2571.38	292.11	104.51	115.09	939.77	>24192
3/28/2018 1:04	18	0.29	34.55	10.71	23.84	2538.21	349.90	124.29	117.29	1045.09	>24192
3/28/2018 1:14	19	0.30	44.75	21.97	22.78	2389.25	288.41	140.64	112.21	948.52	>24192

3/28/2018 1:44	20	0.31	29.05	18.24	10.81	2159.61	232.06	192.50	98.33	866.48	24191.7
3/28/2018 1:44	20LD	0.31									17328.7
3/28/2018 2:14	21	3.15	604.73	111.46	493.28	2367.46	646.22	269.27	102.73	562.55	24191.7
3/28/2018 2:44	22	7.12	349.02	65.31	283.72	1769.84	469.37	157.30	126.43	480.68	17328.7
3/28/2018 3:14	23	12.49	738.85	113.53	625.32	2151.19	1231.89	145.47	178.92	643.92	>24192
3/28/2018 3:44	24	9.28	536.20	92.38	443.82	2394.46	708.33	135.50	233.60	1066.09	>24192
3/28/2018 4:25	25	1.15	139.27	29.02	110.25	2128.82	307.94	244.51	266.78	1852.05	>24193
3/28/2018 4:25	25LD	1.15									24191.7
3/28/2018 5:30	26	0.54	42.80	32.18	10.62	2765.14	305.27	293.57	209.39	1994.69	19862.8

LD = Lab duplicate
FD = Field duplicate
SSC = Suspended Sediment Concentrations in 1 L sample.

Summary of water quality variables measured during storm event 2.

Time [CST] [MM/DD/YYYY HH:MM:SS]	**Sample**	**Discharge [m³/s]**	**TSS [mg/L]**	**VSS [mg/L]**	**NVSS [mg/L]**	**TN [µg/L]**	**TP [µg/L]**	**NH_4+-N [µg/L]**	**SRP [µg/L]**	**NO_3^--N [µg/L]**	***E. coli* (MPN/ 100mL)**
3/28/2018 9:45	1	0.64	143.32	45.05	98.27	2234.46	292.18	122.89	74.86	1214.93	9804
3/28/2018 9:48	2	0.76	115.93	37.22	78.70	2231.69	269.02	134.00	65.76	1249.72	6867
3/28/2018 9:51	3	0.98	166.29	62.92	103.37	2372.04	287.99	142.97	66.27	1003.16	9208
3/28/2018 9:54	4	1.37	215.96	50.02	165.94	2272.07	343.91	138.03	56.31	767.21	4884
3/28/2018 9:57	5	1.77	278.58	64.79	213.79	1714.49	365.88	89.36	51.68	465.20	7270
3/28/2018 10:00	6	2.16	242.65	74.63	168.02	1778.43	319.95	71.98	50.48	385.61	8664
3/28/2018 10:03	7	2.49	255.30	49.94	205.36	1228.63	437.59	73.55	88.43	461.19	15530.7
3/28/2018 10:08	8	3.05	275.35	53.39	221.96	1865.99	556.83	87.68	139.09	663.55	24191.7
3/28/2018 10:13	9	3.15	239.69	46.84	192.86	1911.65	568.01	94.64	140.81	724.67	24191.7
3/28/2018 10:18	10	2.95	246.18	50.54	195.64	2123.27	595.97	94.75	138.74	751.00	>24192
3/28/2018 10:18	10LD	2.95									>14192
3/28/2018 10:23	11	2.59	284.81	51.58	233.23	1875.36	640.71	89.25	155.92	768.75	>24192

3/28/2018 10:28	12	2.11	301.55	53.64	247.90	2210.24	692.24	119.53	180.99	813.21	>24192
3/28/2018 10:33	13	1.79	259.43	45.15	214.28	2118.72	675.27	122.67	199.19	849.71	>24192
3/28/2018 10:33	13FD	1.79	258.39	43.07	215.32	2131.92	690.25	111.12	204.69	943.64	>24192
3/28/2018 10:33	13FD - SSC	1.79	255.18	50.53	204.65						
3/28/2018 10:43	14	1.42	210.62	38.05	172.57	2263.76	612.35	123.46	230.62	1118.63	24191.7
3/28/2018 10:53	15	1.22	245.33	51.57	193.76	2249.11	616.55	119.53	232.85	1111.71	24191.7
3/28/2018 11:03	16	1.16	130.25	27.93	102.32	2210.51	466.15	136.24	232.34	1217.67	19862.8
3/28/2018 11:13	17	1.16	98.13	25.00	73.13	2501.50	424.01	141.51	234.40	1511.39	24191.7
3/28/2018 11:23	18	1.12	90.50	26.24	64.26	2288.30	419.41	163.15	245.05	1627.69	19996.5
3/28/2018 11:33	19	1.01	71.55	22.50	49.04	2443.37	395.05	195.45	235.43	1715.08	>24192
3/28/2018 12:03	20	0.49	41.49	16.90	24.59	2785.05	317.55	294.36	203.49	1974.66	15530.7
3/28/2018 12:03	20LD	0.49									14136
3/28/2018 12:33	21	0.33	28.49	17.07	11.42	3133.32	266.02	305.91	178.93	2334.71	15530.7
3/28/2018 13:03	22	0.29	23.13	13.28	9.85	3105.01	230.47	330.91	154.37	2610.23	14136
3/28/2018 13:33	23	0.26	14.50	11.23	3.27	3597.27	209.10	312.19	130.84	2679.48	9804
3/28/2018 14:03	24	0.27	10.10	12.84	0	3504.29	166.95	179.30	121.23	2872.73	9804

LD = Lab duplicate
FD = Field duplicate
SSC = Suspended Sediment Concentrations in 1 L sample.

Summary of water quality variables measured during storm event 3.

Time [CST] [MM/DD/YYYY HH:MM:SS]	Sample	Discharge [m^3/s]	TSS [mg/L]	VSS [mg/L]	NVSS [mg/L]	TN [µg/L]	TP [µg/L]	NH_4^+-N [µg/L]	SRP [µg/L]	NO_3^--N [µg/L]	*E. coli* (MPN/ 100mL)
4/7/2018 0:25	1	0.49	434.48	186.41	248.08	4377.00	734.17	210.14	10.50	452.11	>48384
4/7/2018 0:28	2	0.75	343.54	147.22	196.32	5270.20	742.73	107.08	13.79	447.03	>48384
4/7/2018 0:31	3	0.86	240.64	112.94	127.70	4792.86	497.35	107.98	17.76	415.52	>48384
4/7/2018 0:34	4	0.65	225.49	119.71	105.79	4452.50	605.02	81.85	20.01	375.58	>48384
4/7/2018 0:37	5	0.43	136.23	71.59	64.64	3923.88	486.21	98.56	15.51	429.90	>48384

4/7/2018 0:40	6	0.22	105.94	59.16	46.77	3906.96	451.18	100.13	17.76	455.68	>48384
4/7/2018 0:45	7	0.15	73.58	50.04	23.54	3385.84	391.08	110.22	13.79	687.85	>48384
4/7/2018 0:50	8	0.08	56.86	39.09	17.78	3448.88	339.14	130.86	8.25	605.44	>48384
4/7/2018 0:55	9	0.07	63.60	51.50	12.10	3101.97	337.95	131.19	10.16	867.01	>48384
4/7/2018 1:00	10	0.05	35.99	29.59	6.40	3014.51	304.91	61.55	12.58	938.95	>48384
4/7/2018 1:00	10LD										>48384
4/7/2018 1:05	11	0.04	28.16	24.32	3.84	2825.46	254.16	159.90	4.10	1045.15	>48384
4/7/2018 1:10	12	0.03	23.91	21.30	2.61	2600.98	197.24	163.04	7.04	1240.36	>48384
4/7/2018 1:20	13	0.03	16.03	12.96	3.07	2708.06	144.31	275.97	17.07	1446.37	8748
4/7/2018 1:30	14	0.04	14.63	10.32	4.31	2359.07	100.33	229.43	17.42	1614.13	>48384
4/7/2018 1:40	15	0.04	10.19	8.17	2.02	2322.70	69.48	341.12	13.61	1718.22	>48384
4/7/2018 1:50	16	0.03	9.27	8.49	0.78	2281.81	71.47	275.63	8.43	1845.01	>48384
4/7/2018 2:00	17	0.03	6.43	6.84	0	2338.43	69.88	232.90	6.70	1821.07	>48384
4/7/2018 2:10	18	0.02	6.65	7.12	0	2195.68	33.66	389.23	10.67	1939.26	15402
4/7/2018 2:40	19	0.03	6.15	6.35	0	2503.84	60.72	378.01	7.04	1898.95	>48384
4/7/2018 3:10	20	0.03	2.03	4.20	0	2417.01	22.91	460.55	9.64	2032.55	1401
4/7/2018 3:10	20LD										1119
4/7/2018 3:40	21	0.03	1.28	4.43	0	2131.69	20.33	652.08	12.23	2041.95	789
4/7/2018 4:10	22	0.03	2.10	3.48	0	2120.81	20.92	687.97	9.46	2140.91	669
4/7/2018 4:40	23	0.03	0.86	3.45	0	2415.19	20.92	651.19	7.39	2177.44	384
4/7/2018 5:10	24	0.03	0.99	4.16	0	2274.13	15.75	268.34	7.22	2180.47	1017

LD = Lab duplicate
FD = Field duplicate

.

Summary of water quality variables measured during storm event 4.

Time [CST] [MM/DD/YYYY HH:MM:SS]	Sample	Discharge [m^3/s]	TSS [mg/L]	VSS [mg/L]	NVSS [mg/L]	TN [µg/L]	TP [µg/L]	NH_4^+-N [µg/L]	SRP [µg/L]	NO_3^--N [µg/L]	Turbidity (NTU) (a)	*E. coli* (MPN/ 100mL)
4/25/2018 16:32	1	0.19	179.72	65.64	114.08	4881.86	608.17	348.07	147.23	2190.95	217.05	8290
4/25/2018 16:32	1LD	0.19										27375

4/25/2018 16:35	2	0.22	185.13	63.73	121.40	5095.41	607.57	309.88	145.19	2229.39	214.13	40820
4/25/2018 16:38	3	0.25	191.98	68.89	123.09	4605.60	645.03	261.47	132.75	2019.65	211.21	120958.5
4/25/2018 16:41	4	0.28	173.31	60.90	112.40	3965.14	585.50	225.11	142.63	1701.75	208.29	77653.5
4/25/2018 16:41	4FD	0.28	187.42	66.75	120.67	4146.04	680.87	370.54	204.14	1623.89	208.29	5270
4/25/2018 16:41	4FD -SES	0.28	195.80	65.23	130.58							
4/25/2018 16:44	5	0.28	169.22	59.06	110.16	3964.42	589.55	207.75	155.07	1562.27	205.37	64982.5
4/25/2018 16:47	6	0.29	164.24	58.44	105.80	3463.23	521.31	194.05	154.73	1263.10	209.57	64982.5
4/25/2018 16:52	7	0.29	148.81	54.99	93.82	3510.65	514.56	177.42	151.32	1199.03	222.51	23055
4/25/2018 16:57	8	0.28	126.36	44.84	81.52	3074.31	427.16	161.34	148.08	1234.98	235.44	32440
4/25/2018 17:02	9	0.26	107.48	39.37	68.11	2534.74	442.74	184.73	154.73	940.53	225.59	27375
4/25/2018 17:07	10	0.24	94.05	35.90	58.15	2682.00	432.01	164.45	153.36	971.59	181.19	17240
4/25/2018 17:07	10LD	0.24										19865
4/25/2018 17:12	11	0.21	83.46	33.24	50.22	2615.46	341.70	223.83	162.05	964.70	136.79	36350
4/25/2018 17:17	12	0.19	72.66	30.10	42.55	2507.16	360.93	215.06	152.51	979.95	107.84	49020
4/25/2018 17:27	13	0.20	54.75	22.33	32.42	2417.19	335.62	228.58	146.72	1025.89	96.76	24420
4/25/2018 17:37	14	0.27	96.19	36.27	59.92	2540.40	345.75	210.86	149.44	943.90	148.58	10230
4/25/2018 17:47	15	0.40	443.47	140.59	302.88	2851.71	561.80	122.06	118.95	575.73	196.67	9675
4/25/2018 17:57	16	0.37	147.91	45.59	102.32	2296.08	408.72	107.44	124.91	548.80	124.80	10490
4/25/2018 18:07	17	0.31	82.67	30.74	51.94	2010.12	308.69	99.04	112.30	531.10	87.89	9300
4/25/2018 18:17	18	0.22	62.47	22.41	40.06	1706.55	285.00	124.62	109.06	589.52	67.42	5890
4/25/2018 18:47	19	0.04	24.69	10.47	14.23	1811.79	175.45	197.52	92.88	1020.62	44.49	8080
4/25/2018 19:17	20	0.03	9.76	6.91	2.85	1673.11	100.94	162.62	66.98	1441.03	12.32	2955
4/25/2018 19:17	20LD	0.03										3190
4/25/2018 19:47	21	0.03	11.05	7.29	3.76	1850.37	61.86	328.34	37.16	1713.64	6.11	1250
4/25/2018 20:17	22	0.03	6.51	7.49	0	1948.85	34.32	755.33	32.05	1836.19	4.68	935
4/25/2018 20:47	23	0.03	3.83	4.55	0	2049.09	35.33	948.64	25.23	1936.04	5.66	2020
4/25/2018 21:17	24	0.03	2.48	4.07	0	2069.12	29.86	920.87	22.33	1998.15	5.78	1565

LD = Lab duplicate
FD = Field duplicate
SSC = Suspended Sediment Concentrations in 1 L sample.
(a) = Edwards Aquifer Authority, unpublished.

Summary of water quality variables measured during storm event 5.

Time [CST] [MM/DD/YYYY HH:MM:SS]	Sample	Discharge [m3/s]	TSS [mg/L]	VSS [mg/L]	NVSS [mg/L]	TN [µg/L]	TP [µg/L]	NH_4^+-N [µg/L]	SRP [µg/L]	NO_3^--N [µg/L]	Turbidity (NTU) (a)	Turbidity (NTU) (b)	*E. coli* (MPN/ 100mL)
5/4/2018 9:31	1	0.57	420.24	150.22	270.02	6278.29	931.99	502.18	291.33	1974.52	104.21	110.37	30655
5/4/2018 9:31	1LD	0.57											25860
5/4/2018 9:34	2	0.88	449.89	155.20	294.69	5316.02	1008.69	873.01	253.66	1918.89	103.30	168.18	13615
5/4/2018 9:34	2LD	0.88	592.08	233.69	358.39								
5/4/2018 9:37	3	1.19	363.26	111.60	251.66	4764.57	683.91	740.93	179.49	1306.80	102.39	166.30	13615
5/4/2018 9:40	4	1.50	212.08	64.59	147.49	4042.63	606.40	756.64	152.41	852.54	101.49	103.02	9250
5/4/2018 9:43	5	1.65	298.02	112.74	185.27	3282.19	475.60	502.30	132.23	577.35	100.58	94.51	9520
5/4/2018 9:46	6	1.80	263.10	82.03	181.08	3456.78	467.33	312.78	112.55	460.00	105.07	78.72	10715
5/4/2018 9:51	7	2.03	243.74	68.17	175.58	2326.27	405.16	225.87	90.68	363.33	130.55	75.00	15380
5/4/2018 9:56	8	2.11	287.30	70.86	216.44	1884.66	496.39	208.56	100.61	328.65	156.03	106.50	30655
5/4/2018 10:01	9	2.10	279.15	58.59	220.56	2055.86	538.38	202.18	102.46	397.39	176.98	136.65	32440
5/4/2018 10:06	10	1.70	406.92	77.26	329.66	2555.75	728.92	220.59	124.99	503.15	179.88	202.74	36350
5/4/2018 10:06	10LD	1.70	264.84	64.74	200.10								40820
5/4/2018 10:11	11	1.36	285.13	58.40	226.74	2368.89	597.12	250.05	124.32	660.65	182.78	183.35	30655
5/4/2018 10:16	12	1.35	188.45	39.48	148.97	1820.11	457.23	227.34	116.92	502.76	181.23	117.31	34335
5/4/2018 10:26	13	1.29	142.25	30.37	111.88	1610.14	382.35	246.74	117.43	489.27	142.57	84.70	46040
5/4/2018 10:36	14	1.17	129.22	28.15	101.07	2282.67	334.71	260.36	116.92	751.69	115.04	83.39	36350
5/4/2018 10:46	15	0.99	101.77	24.90	76.87	1675.35	363.17	266.13	119.95	740.65	95.56	65.67	24420
5/4/2018 10:56	16	0.82	91.22	24.79	66.42	1840.54	310.69	259.87	116.25	650.78	80.62	51.65	20530
5/4/2018 11:06	17	0.53	71.60	20.29	51.32	1632.40	276.58	251.03	108.85	682.28	70.07	44.40	20530
5/4/2018 11:16	18	0.33	47.92	14.05	33.87	1577.25	246.10	250.17	116.92	819.37	63.26	37.28	24420
5/4/2018 11:46	19	0.44	59.43	17.76	41.68	1635.60	284.65	264.66	116.58	761.83	91.34	56.75	18270
5/4/2018 12:16	20	0.78	60.11	17.02	43.09	1239.48	260.43	188.80	105.48	564.98	80.55	50.27	8320

5/4/2018 12:16	20LD	0.78											12405
5/4/2018 12:46	21	0.74	55.64	17.42	38.22	1247.05	237.42	172.23	98.76	484.53	67.66	46.86	12405
5/4/2018 13:16	22	0.82	75.45	19.31	56.15	1474.12	261.64	161.30	107.67	528.29	74.93	45.55	21760
5/4/2018 13:46	23	0.46	38.40	12.83	25.57	1434.24	222.69	164.13	103.30	631.93	48.34	29.34	13775
5/4/2018 14:16	24	0.25	28.95	10.69	18.26	1614.97	278.40	156.88	100.77	694.60	42.36	26.80	20530
5/4/2018 14:16	24FD	0.25	21.92	9.44	12.48	1200.91	171.82	139.58	99.93	698.89	42.36	26.80	11795
5/4/2018 14:16	24FD - SSC	0.25	20.15	6.67	13.48								

LD = Lab duplicate
FD = Field duplicate
SSC = Suspended Sediment Concentrations in 1 L sample.
(a) = Edwards Aquifer Authority, unpublished.
(b) = Edwards Aquifer Research and Data Center, unpublished.

Summary of water quality variables measured during storm event 6.

Time [CST] [MM/DD/YYYY HH:MM:SS]	Sample	Discharge [m3/s]	TSS [mg/L]	VSS [mg/L]	NVSS [mg/L]	TN [µg/L]	TP [µg/L]	NH_4^+-N [µg/L]	SRP [µg/L]	NO_3^-N [µg/L]	Turbidity (NTU) (a)	Turbidity (NTU) (b)	*E. coli* (MPN/ 100mL)
6/16/2018 15:01	1	0.96	841.97	211.34	630.64	6472.34	1701.92	77.01	135.90	1268.56	274.50	218.50	
6/16/2018 15:01	1LD	0.96	1123.77	320.89	802.88	5367.37	1667.52	83.24	141.70	1270.06	274.50	218.50	>120950
6/16/2018 15:04	2	1.33	1155.87	759.77	396.10	5219.83	1354.32	115.99	142.55	1380.84	327.00	182.85	>120950
6/16/2018 15:07	3	1.17	359.58	87.25	272.33	4958.45	962.20	76.91	145.45	1107.92	326.73	214.94	>120950
6/16/2018 15:10	4	1.05	320.02	86.07	233.95	5414.62	971.31	71.81	156.01	1255.56	299.55	183.73	>120950
6/16/2018 15:13	5	1.04	332.81	111.35	221.46	4577.49	855.57	69.77	162.32	1159.27	269.67	170.53	>120950
6/16/2018 15:16	6	1.34	239.91	64.83	175.07	3820.18	765.33	100.99	191.47	988.23	229.15	132.12	>120950
6/16/2018 15:21	7	1.26	200.85	58.23	142.62	3211.47	583.24	109.15	168.12	768.71	142.16	91.61	>120950
6/16/2018 15:26	8	1.41	132.92	36.45	96.47	2945.48	489.56	123.33	160.28	787.74	124.28	75.40	>120950
6/16/2018 15:26	8LD	1.41	160.10	52.02	108.08	2819.33	490.16	102.42	163.68	792.72	124.28	75.39	>120950
6/16/2018 15:31	9	0.36	169.99	50.70	119.28	2960.15	551.27	89.36	152.61	803.62	133.36	93.92	>120950
6/16/2018 15:36	10	0.28	101.06	29.50	71.56	2980.68	490.77	62.02	153.97	864.05	116.74	69.30	>120950
6/16/2018 15:36	10LD	0.28											5530

6/16/2018 15:36	10FD	0.28	107.31	26.86	80.45	2909.35	479.85	194.44	226.58	967.37	116.74	69.30	7105
6/16/2018 15:36	10FD – SSC	0.28	107.79	30.05	77.74						116.74	69.30	
6/16/2018 15:41	11	0.11	71.75	22.43	49.32	2734.63	445.65	110.27	156.36	827.86	97.98	57.15	>120950
6/16/2018 15:46	12	0.10	62.04	21.03	41.01	2719.76	417.73	116.39	160.79	991.22	79.15	49.42	>120950
6/16/2018 15:56	13	0.05	43.84	15.76	28.08	2856.90	378.48	135.78	158.57	1104.38	62.14	39.84	>120950
6/16/2018 16:06	14	0.03	32.06	13.27	18.79	2932.45	342.46	162.51	146.13	1233.87	48.94	32.43	>120950
6/16/2018 16:16	15	0.02	33.48	17.59	15.89	2861.57	302.20	181.79	145.28	1286.44	35.16	24.74	>120950
6/16/2018 16:26	16	0.02	31.15	15.76	15.39	2863.02	286.89	193.84	135.33	1317.52	32.30	21.39	
6/16/2018 16:36	17	0.02	28.82	13.92	14.89	2864.47	271.58	205.89	125.39	1348.61	29.43	18.14	
6/16/2018 16:46	18	0.01	26.48	12.09	14.39	2865.92	256.27	217.94	115.45	1379.70	26.56	15.11	
6/16/2018 17:16	19	0.03	19.49	6.60	12.89	2870.26	210.34	254.09	85.62	1472.96	17.96	9.65	
6/16/2018 17:46	20	0.03	12.50	1.11	11.39	2874.60	164.41	290.24	55.80	1566.22	9.35	6.59	34335
6/16/2018 18:16	21	0.03	6.44	1.11	5.33	2793.73	156.12	360.12	70.97	1869.85	14.25	10.00	55992.5
6/16/2018 18:46	22	0.03	3.81	1.11	2.70	2535.30	132.24	321.45	60.23	1715.79	14.58	9.82	28970
6/16/2018 19:16	23	0.03	2.37	1.11	1.27	2335.97	111.81	326.86	60.91	1705.44	13.11	9.14	14545
6/16/2018 19:46	24	0.03	2.55	1.11	1.44	2162.51	109.78	330.53	54.26	1572.97	12.51	8.53	13065
6/16/2018 19:46	24LD	0.03											16275

LD = Lab duplicate
FD = Field duplicate
SSC = Suspended Sediment Concentrations in 1 L sample.
(a) = Edwards Aquifer Authority, unpublished.
(b) = Edwards Aquifer Research and Data Center, unpublished.

Summary of water quality variables measured during storm event 7.

Time [CST] [MM/DD/YYYY HH:MM:SS]	Sample	Discharge [m3/s]	TSS [mg/L]	VSS [mg/L]	NVSS [mg/L]	TN [µg/L]	TP [µg/L]	NH_4^+-N [µg/L]	SRP [µg/L]	NO_3^--N [µg/L]	Turbidity (NTU) (a)	Turbidity (NTU) (b)	*E. coli* (MPN/ 100mL)
6/19/2018 10:13	1	0.38	78.93	29.69	49.24	2192.30	333.96	32.99	72.69	1087.30	94.64	52.83	25860
6/19/2018 10:13	1LD	0.38											25860
6/19/2018 10:16	2	0.41	88.82	32.37	56.45	2111.25	470.94	28.29	84.11	887.50	112.41	58.90	18270
6/19/2018 10:19	3	0.57	91.73	37.57	54.16	1657.47	323.09	24.49	83.59	887.50	88.53	60.01	32440

6/19/2018 10:22	4	0.75	75.91	20.34	55.57	1590.46	294.80	27.29	83.42	484.41	75.43	50.79	24420
6/19/2018 10:25	5	0.58	97.73	56.02	41.71	1414.91	280.65	17.99	89.39	432.04	67.87	43.43	30655
6/19/2018 10:28	6	0.45	68.08	26.78	41.30	1448.54	268.35	18.29	79.16	399.03	62.13	38.87	38505
6/19/2018 10:28	6LD	0.45				1411.51	289.26	28.89	78.31	419.43	62.13	38.87	
6/19/2018 10:33	7	0.36	42.83	19.66	23.17	1035.72	238.20	25.99	77.80	363.73	51.75	30.77	28970
6/19/2018 10:33	7LD	0.36	42.88	19.67	23.21						51.75	30.77	
6/19/2018 10:38	8	0.36	36.02	15.30	20.72	1047.80	219.13	25.09	79.16	358.55	46.23	29.26	32440
6/19/2018 10:43	9	0.51	43.70	17.33	26.37	951.53	205.60	20.29	78.31	344.85	46.84	29.46	21760
6/19/2018 10:48	10	0.44	37.99	15.67	22.32	1029.05	212.37	22.69	75.24	289.96	44.77	29.11	30655
6/19/2018 10:48	10LD	0.44											24420
6/19/2018 10:53	11	0.42	37.51	15.86	21.64	1380.95	201.50	22.49	74.90	320.52	45.67	30.23	23055
6/19/2018 10:58	12	0.87	90.50	28.87	61.63	981.18	276.34	17.19	73.54	318.77	66.19	46.37	24420
6/19/2018 11:08	13	0.89	64.93	28.02	36.90	1202.19	205.19	14.49	59.40	294.88	52.65	35.22	20530
6/19/2018 11:18	14	0.37	28.97	12.56	16.41	743.78	147.98	24.69	60.76	363.18	37.29	23.58	21760
6/19/2018 11:28	15	0.35	21.53	10.66	10.87	762.46	161.51	23.49	61.78	335.58	34.03	21.28	23055
6/19/2018 11:38	16	0.77	38.39	19.40	19.00	883.22	158.44	22.09	56.84	362.64	35.19	22.32	27375
6/19/2018 11:38	16LD					899.41	166.85	22.79	60.93	324.56	35.19	22.32	
6/19/2018 11:48	17	0.46	26.53	12.34	14.19	720.85	139.57	27.99	60.59	368.97	313.10	21.13	28970
6/19/2018 11:48	17LD	0.46	35.10	22.36	12.74						313.10	21.13	
6/19/2018 11:58	18	0.37	17.75	9.14	8.62	648.68	143.27	19.79	58.89	365.80	613.40	19.18	24420
6/19/2018 12:28	19	0.09	12.87	7.08	5.79	943.50	117.84	46.08	63.32	700.63	168.12	18.03	30655
6/19/2018 12:58	20	0.06	12.64	6.95	5.68	1306.17	109.43	118.68	56.84	1034.43	33.36	18.05	21760
6/19/2018 12:58	20LD	0.06											19365
6/19/2018 13:28	21	0.05	10.87	6.97	3.90	1500.92	110.66	180.58	51.05	1122.82	29.21	16.92	15380
6/19/2018 13:28	21FD	0.05	8.88	5.72	3.17	1504.25	104.72	191.18	57.18	1160.19	29.21	16.92	18270
6/19/2018 13:28	21FD- SSC	0.05	8.70	4.77	3.93						29.21	16.92	18270
6/19/2018 13:58	22	0.04	8.16	5.95	2.20	1516.60	77.65	235.78	44.91	1238.92	24.21	14.08	13775
6/19/2018 14:28	23	0.04	5.85	4.89	0.96	1431.11	65.96	220.38	39.29	1317.16	20.92	11.62	10065
6/19/2018 14:58	24	0.04	4.95	4.52	0.42	1451.03	62.89	222.38	36.39	1208.80	18.01	9.78	7250

LD = Lab duplicate
FD = Field duplicate

SSC = Suspended Sediment Concentrations in 1 L sample.
(a) = Edwards Aquifer Authority, unpublished.
(b)= Edwards Aquifer Research and Data Center, unpublished.

Summary of water quality variables measured during storm event 8.

Time [CST] [MM/DD/YYYY HH:MM:SS]	Sample	Discharge [m3/s]	TSS [mg/L]	VSS [mg/L]	NVSS [mg/L]	TN [µg/L]	TP [µg/L]	NH_4^+-N [µg/L]	SRP [µg/L]	NO_3^--N [µg/L]	Turbidity (NTU) (a)	Turbidity (NTU) (b)	*E. coli* (MPN/ 100mL)
7/4/2018 14:07	Base line	Baseflow	4.27	3.65	0.62	1933.63	19.27	136.61	10.94	1918.61	11.30	4.16	<50
7/4/2018 14:31	1	1.09	711.70	153.50	558.20	4925.69	1333.03	228.90	128.40	1270.95	70.43	162.25	<120960
7/4/2018 14:31	1FD	1.09	731.23	148.32	582.91	4910.95	1453.78	301.85	215.11	1717.25	70.43	162.25	38505
7/4/2018 14:31	1FD-SSC	1.09	882.36	184.02	698.34						70.43	162.25	
7/4/2018 14:34	2	2.14	437.45	91.53	345.92	3396.71	955.56	213.66	141.53	981.72	264.84	107.90	38505
7/4/2018 14:37	3	2.56	332.12	90.09	242.03	2402.19	644.21	149.90	128.75	580.54	284.18	155.22	5230
7/4/2018 14:37	3LD	2.56	641.74	244.15	397.59	2485.25	614.44	112.72	128.23	543.58	284.18	155.22	
7/4/2018 14:40	4	2.61	255.06	44.68	210.38	2037.04	542.15	62.04	113.20	510.63	216.18	72.85	4925
7/4/2018 14:43	5	2.00	189.92	32.92	156.99	1739.64	478.89	51.56	114.93	388.38	193.02	123.47	4025
7/4/2018 14:46	6	2.04	152.17	27.67	124.50	1282.50	395.72	51.99	104.05	375.93	171.20	81.09	3120
7/4/2018 14:51	7	2.00	152.91	28.35	124.56	1207.99	372.51	40.86	106.29	360.01	171.32	84.30	4800
7/4/2018 14:56	8	2.21	317.94	53.41	264.53	1836.09	599.65	64.74	127.71	539.89	284.02	163.60	9675
7/4/2018 15:01	9	2.01	281.09	44.68	236.41	1834.82	632.10	57.61	109.75	610.62	302.08	203.08	14545
7/4/2018 15:06	10	1.30	197.51	33.95	163.56	1863.91	539.07	52.10	120.45	719.87	234.80	145.55	10710
7/4/2018 15:11	11	1.23	158.99	28.72	130.27	1780.98	470.68	47.12	119.42	820.52	186.98	106.12	11410
7/4/2018 15:16	12	1.19	146.33	33.89	112.45	1833.80	420.77	53.28	125.81	911.48	142.06	114.58	12445
7/4/2018 15:26	13	0.96	147.08	30.12	116.97	1824.29	408.66	60.63	123.74	890.71	141.34	92.49	12405
7/4/2018 15:26	13LD	0.96	146.88	33.58	113.30	2067.72	429.60	61.07	123.05	932.69	141.34	92.49	
7/4/2018 15:36	14	1.07	94.71	21.22	73.50	1671.38	338.01	59.44	115.62	890.32	124.50	78.46	9590
7/4/2018 15:46	15	0.86	81.36	19.11	62.24	1458.00	326.92	58.15	111.30	749.40	112.78	71.55	5215
7/4/2018 15:56	16	1.04	119.51	25.05	94.45	1516.69	389.76	44.42	106.46	500.16	113.66	74.48	4275

7/4/2018 16:06	17	0.86	64.93	15.43	49.50	1067.78	278.25	18.27	98.52	516.97	95.23	57.47	4180
7/4/2018 16:16	18	0.80	56.18	15.75	40.43	1198.62	280.30	30.05	105.77	574.76	94.38	54.01	4065
7/4/2018 16:46	19	0.38	49.99	14.20	35.79	1451.94	297.55	42.91	111.47	793.91	96.55	60.47	5250
7/4/2018 17:16	20	0.29	41.57	11.30	30.27	1412.90	256.48	70.47	112.85	779.53	85.86	50.10	4065
7/4/2018 17:16	20LD	0.29											3615
7/4/2018 17:46	21	0.23	38.02	10.74	27.28	1472.92	248.06	78.57	112.34	965.36	82.47	49.80	4940
7/4/2018 18:16	22	0.16	28.55	8.74	19.81	1559.94	219.10	148.17	105.25	1094.71	65.06	36.60	3515
7/4/2018 18:46	23	0.08	20.40	7.50	12.91	1555.09	175.97	174.32	95.06	1103.31	50.73	27.30	3220
7/4/2018 19:16	24	0.05	16.16	6.67	9.49	1527.02	154.82	201.77	88.33	1149.75	33.87	20.27	3570

LD = Lab duplicate
FD = Field duplicate
SSC = Suspended Sediment Concentrations in 1 L sample.
(a) = Edwards Aquifer Authority, unpublished. (b)= Edwards Aquifer Research and Data Center, unpublished.

Summary of water quality variables measured during storm event 9.

Time [CST] [MM/DD/YYYY HH:MM:SS]	Sample	Discharge [m3/s]	TSS [mg/L]	VSS [mg/L]	NVSS [mg/L]	TN [µg/L]	TP [µg/L]	NH_4^+-N [µg/L]	SRP [µg/L]	NO_3^--N [µg/L]	Turbidity (NTU) (a)	Turbidity (NTU) (b)	*E. coli* (MPN/ 100mL)
7/7/2018 16:10	1	0.34	345.65	72.56	273.09	2852.16	692.57	121.73	55.34	701.54	139.40	101.72	5195
7/7/2018 16:13	2	1.84	259.47	1.11	258.37	2269.22	536.96	115.94	55.34	673.82	115.20	169.24	4665
7/7/2018 16:16	3	2.04	218.02	41.65	176.37	2112.58	455.30	88.24	53.12	470.74	107.23	128.28	4045
7/7/2018 16:16	3LD	2.04											3455
7/7/2018 16:19	4	2.15	282.58	47.94	234.65	1807.73	558.39	92.77	54.83	457.93	131.73	157.61	11910
7/7/2018 16:22	5	2.56	334.90	65.61	269.29	1490.18	531.17	77.39	55.34	268.60	138.94	132.18	14255
7/7/2018 16:22	5LD	2.56				1773.42	570.83	72.23	58.08	295.44	138.94	132.18	
7/7/2018 16:25	6	3.36	303.16	57.19	245.97	2150.59	537.60	84.34	64.75	242.93	137.50	158.80	17240
7/7/2018 16:30	7	2.12	364.56	54.03	310.53	1627.47	712.72	65.07	70.91	329.77	192.60	237.82	21760
7/7/2018 16:35	8	2.01	557.27	77.35	479.92	1966.44	1378.25	46.11	65.09	425.54	357.80	378.21	17240
7/7/2018 16:35	8LD	2.01											15380
7/7/2018 16:40	9	1.99	550.07	82.94	467.14	2057.23	1044.09	54.53	74.50	388.27	284.70	403.74	24420

7/7/2018 16:45	10	2.34	639.62	85.48	554.14	1884.13	1495.27	52.95	81.00	427.65	389.30	498.62	25860
7/7/2018 16:50	11	2.07	633.70	82.63	551.07	2556.35	1724.19	48.63	100.84	447.17	439.30	511.24	23055
7/7/2018 16:55	12	1.25	579.83	73.56	506.27	2160.08	1749.91	53.48	101.01	572.11	453.80	515.67	25860
7/7/2018 17:05	13	1.16	572.24	69.16	503.08	2021.16	1655.17	50.11	124.62	768.42	390.90	446.28	13775
7/7/2018 17:15	14	0.59	404.97	51.58	353.39	2116.73	1322.82	46.84	133.34	720.34	326.60	422.03	17240
7/7/2018 17:25	15	0.39	354.15	46.83	307.32	1559.23	1205.10	45.90	144.80	703.54	299.80	392.40	15390
7/7/2018 17:25	15LD					1308.48	754.73	72.02	144.12	698.94	299.80	392.40	
7/7/2018 17:35	16	0.32	312.42	42.16	270.25	1374.95	1081.38	88.55	152.84	718.07	275.60	331.73	16275
7/7/2018 17:45	16LD	0.27	299.74	40.64	259.10						243.20	334.00	
7/7/2018 17:45	17	0.27	250.95	36.90	214.05	1557.66	948.28	61.80	155.41	648.25	243.20	334.00	10490
7/7/2018 17:55	18	0.23	232.59	35.16	197.43	1437.15	702.65	55.38	150.45	753.51	214.30	257.95	10490
7/7/2018 18:25	19	0.11	137.33	27.91	109.42	1192.99	540.39	76.97	162.25	823.16	164.70	180.92	9300
7/7/2018 18:55	20	0.08	104.50	18.97	85.53	1398.76	489.59	96.24	140.53	941.50	123.60	149.49	6180
7/7/2018 18:55	20LD	0.08											13065
7/7/2018 19:25	21	0.06	86.55	15.38	71.18	789.62	203.23	185.67	127.70	940.78	110.60	121.26	6880
7/7/2018 19:55	22	0.05	72.47	13.51	58.95	1237.48	306.76	248.97	116.92	1025.68	87.54	99.74	3855
7/7/2018 20:25	23	0.05	58.05	12.40	45.66	1321.92	308.69	254.34	109.40	1065.67	72.64	76.91	3815
7/7/2018 20:55	24	0.05	42.51	10.62	31.89	1273.48	235.60	42.74	96.57	917.99	55.11	57.60	3220
7/7/2018 20:55	24FD	0.05	41.11	8.43	32.68	1292.09	202.38	43.58	106.66	1009.16	55.11	57.60	3635
7/7/2018 20:55	24FD-SSC	0.05	42.22	8.81	33.41						55.11	57.60	

LD = Lab duplicate
FD = Field duplicate
SSC = Suspended Sediment Concentrations in 1 L sample.
(a) = Edwards Aquifer Authority, unpublished.
(b) = Edwards Aquifer Research and Data Center, unpublished.

Summary of water quality variables measured during storm event 10.

Time [CST] [MM/DD/YYYY HH:MM:SS]	Sample	Discharge [m3/s]	TSS [mg/L]	VSS [mg/L]	NVSS [mg/L]	TN [µg/L]	TP [µg/L]	NH_4^+-N [µg/L]	SRP [µg/L]	NO_3^--N [µg/L]	Turbidity (NTU) (a)	Turbidity (NTU) (b)	*E. coli* (MPN/ 100mL)
7/9/2018 10:18	1	0.99	390.59	98.10	292.49	1829.49	606.41	32.32	28.79	480.77	150.58	178.95	9250
7/9/2018 10:18	1LD	0.99											9210
7/9/2018 10:21	2	2.14	287.25	60.58	226.68	1707.92	527.60	76.27	41.15	524.37	149.08	141.27	12445
7/9/2018 10:24	3	2.19	322.15	49.04	273.12	1650.97	513.18	73.80	53.51	351.10	204.22	217.91	21760
7/9/2018 10:27	4	2.15	265.99	47.37	218.62	1261.79	455.71	62.99	53.17	322.91	174.32	183.20	21760
7/9/2018 10:30	5	2.25	211.50	45.60	165.90	1069.89	392.70	123.62	57.74	278.09	101.90	137.64	25860
7/9/2018 10:33	6	2.06	184.26	37.74	146.52	1262.74	373.14	135.96	65.36	389.82	99.90	119.04	43320
7/9/2018 10:33	6LD	2.06	188.42	36.87	151.54	1385.51	373.14	165.22	64.85	366.78	99.90	119.04	
7/9/2018 10:38	7	1.14	168.88	34.31	134.57	1582.86	419.17	141.48	77.21	499.55	98.73	120.33	40820
7/9/2018 10:43	8	0.91	162.11	30.43	131.67	1638.54	461.24	128.91	93.46	526.92	99.78	122.20	70680
7/9/2018 10:48	9	0.48	236.64	44.68	191.96	1716.55	515.95	84.26	104.30	637.04	99.60	136.38	60165
7/9/2018 10:53	10	1.10	191.68	38.07	153.61	1916.69	424.89	109.87	65.87	484.76	111.63	116.07	28970
7/9/2018 10:53	10LD	1.10											30655
7/9/2018 10:58	11	2.27	326.94	72.68	254.26	1256.84	497.78	107.29	59.60	241.98	138.72	135.16	20530
7/9/2018 11:03	12	7.53	665.77	130.83	534.95	1841.09	866.15	66.16	79.41	176.95	225.48	197.67	43320
7/9/2018 11:13	13	7.53	894.38	136.50	757.88	1740.52	1776.72	54.06	95.16	506.31	403.92	524.78	99315
7/9/2018 11:23	14	7.53	1446.16	225.79	1220.37	4521.59	2159.12	61.58	137.65	646.12	552.30	652.61	60165
7/9/2018 11:33	15	3.41	676.85	86.98	589.87	3388.00	1684.28	72.51	177.61	831.57	436.20	524.45	60165
7/9/2018 11:33	15FD	3.41	651.32	84.24	567.08	2657.07	793.47	84.61	186.24	898.88	436.20	524.45	49020
7/9/2018 11:33	15FD- SSC	3.41	763.22	104.71	658.52						436.20	524.45	
7/9/2018 11:43	16	2.22	613.83	85.09	528.74	2217.97	640.19	85.20	164.91	975.48	299.60	323.80	43320
7/9/2018 11:53	17	2.01	303.51	46.63	256.88	2198.19	809.07	86.14	179.81	1181.60	191.30	253.72	30655
7/9/2018 11:53	17LD	2.01	309.46	45.24	264.22	2351.02	804.33	86.14	176.93	1226.02	191.30	253.72	
7/9/2018 12:03	18	1.26	202.75	32.30	170.45	1930.45	635.05	83.90	192.85	1338.19	125.26	154.95	28970
7/9/2018 12:33	19	3.41	165.80	27.89	137.91	2215.50	515.75	89.08	138.50	1315.26	97.33	126.50	32440
7/9/2018 13:03	20	0.57	92.69	19.21	73.49	2264.33	324.55	61.70	139.35	1550.96	51.90	72.30	16275

7/9/2018 13:03	20LD	0.57											14055
7/9/2018 13:33	21	0.30	52.41	11.85	40.56	2225.90	329.10	74.50	170.16	1661.58	42.43	50.11	21760
7/9/2018 14:03	22	0.57	36.93	8.92	28.01	2167.75	251.08	54.64	170.16	1713.53	65.08	39.36	19365
7/9/2018 14:33	23	0.14	30.44	7.43	23.01	2397.31	220.26	68.39	119.03	1741.23	33.64	34.67	16275
7/9/2018 15:03	24	0.08	27.16	6.81	20.35	2345.25	188.07	191.78	103.62	1974.60	33.24	28.55	8965

LD = Lab duplicate
FD = Field duplicate
SSC = Suspended Sediment Concentrations in 1 L sample.
(a) = Edwards Aquifer Authority, unpublished.
(b) = Edwards Aquifer Research and Data Center, unpublished.

Summary of water quality variables measured during storm event 11.

Time [CST] [MM/DD/YYYY HH:MM:SS]	Sample	Discharge [m3/s]	TSS [mg/L]	VSS [mg/L]	NVSS [mg/L]	TN [µg/L]	TP [µg/L]	NH_4^+-N [µg/L]	SRP [µg/L]	NO_3^--N [µg/L]	Turbidity (NTU) (a)	Turbidity (NTU) (b)	*E. coli* (MPN/ 100mL)
8/12/2018 12:08	1	1.20	912.03	195.13	716.90	5025.14	1911.10	40.32	95.38	1595.68	219.42	254.65	>120960
8/12/2018 12:08	1LD	1.20											>120960
8/12/2018 12:11	2	0.97	734.24	148.43	585.81	5361.23	1507.91	93.51	124.01	1847.28	344.04	437.45	>120960
8/12/2018 12:14	3	0.89	560.91	112.74	448.17	4898.01	1339.32	127.94	142.53	1624.13	286.26	335.77	120958.5
8/12/2018 12:17	4	0.48	530.68	109.30	421.38	4814.60	1395.78	150.96	181.11	1567.57	238.16	307.76	64982.5
8/12/2018 12:20	5	0.40	381.77	75.71	306.06	4172.23	907.70	165.07	238.89	1479.56	194.90	252.64	60165.5
8/12/2018 12:23	6	0.38	256.61	50.78	205.83	3582.89	804.92	170.36	206.82	1353.45	156.02	298.95	94314
8/12/2018 12:28	7	0.26	200.29	46.65	153.65	3370.71	638.12	144.09	227.57	1219.59	108.04	136.14	77655
8/12/2018 12:28	7LD					3360.46	607.70	156.16	228.08	1285.30	108.04	136.14	
8/12/2018 12:33	8	0.13	133.75	32.31	101.44	3061.92	537.12	173.14	235.80	1225.41	81.75	103.84	120958.5
8/12/2018 12:33	8LD	0.13	148.76	36.73	112.03						81.75	103.84	
8/12/2018 12:38	9	0.09	95.69	24.71	70.99	2849.43	508.49	173.79	229.28	1262.01	65.98	82.91	70680
8/12/2018 12:43	10	0.05	81.79	20.45	61.34	3253.52	471.12	127.10	195.85	1346.08	57.56	72.86	1965
8/12/2018 12:43	10LD	0.05											120958.5
8/12/2018 12:48	11	0.04	74.07	19.13	54.93	2912.84	451.83	125.43	173.39	1326.12	51.43	66.40	70680

8/12/2018 12:53	12	0.04	61.27	17.33	43.94	2917.12	415.05	132.77	174.08	1277.70	44.62	59.71	77655
8/12/2018 13:03	13	0.03	48.21	14.11	34.11	2695.82	384.24	139.82	173.22	1468.19	33.90	46.03	94314
8/12/2018 13:13	14	0.03	40.41	12.83	27.58	2759.80	342.69	143.07	175.62	1533.52	31.51	40.61	70680
8/12/2018 13:13	14LD					2901.96	346.07	148.45	177.33	1415.18	31.51	40.61	
8/12/2018 13:23	15	0.03	33.75	11.95	21.80	2725.26	323.60	151.89	159.33	1500.41	28.80	34.75	86643.5
8/12/2018 13:23	15LD	0.03	35.85	13.68	22.17						28.80	34.75	
8/12/2018 13:33	16	0.03	27.94	10.19	17.76	2854.78	294.97	155.51	141.67	1600.23	25.52	31.70	94314
8/12/2018 13:43	17	0.04	25.53	10.38	15.14	2765.33	275.29	174.62	123.67	1701.43	25.23	30.95	94314
8/12/2018 13:53	18	0.05	24.29	10.64	13.66	2832.95	263.16	180.01	119.56	1697.33	24.97	29.45	120958.5
8/12/2018 14:23	19	0.11	49.01	16.80	32.20	2201.72	348.85	60.65	132.41	1162.14	49.10	59.07	32440
8/12/2018 14:53	20	0.01	26.74	11.45	15.29	1957.08	258.59	78.29	132.07	1094.37	27.04	35.35	23055
8/12/2018 14:53	20LD	0.01											
8/12/2018 15:23	21	0.02	69.75	18.48	51.27	2291.29	267.73	63.90	113.56	1183.82	21.92	24.17	34335
8/12/2018 15:23	21FD	0.02	30.87	10.78	20.10	2016.15	239.30	110.31	140.47	1232.95	21.92	24.17	46040
8/12/2018 15:23	21FD-SSC	0.02	15.64	6.74	8.90						21.92	24.17	21760
8/12/2018 15:53	22	0.01	12.30	8.18	4.11	2045.09	166.94	66.96	86.64	1328.06	14.94	17.02	46040
8/12/2018 16:23	23	0.00	6.90	5.20	1.70	2063.20	131.15	211.47	71.89	1488.43	10.54	11.25	28970
8/12/2018 16:53	24	0.00	4.20	4.49	-0.29	1879.21	92.98	283.96	47.89	1615.98	7.68	7.23	36350

LD = Lab duplicate
FD = Field duplicate
SSC = Suspended Sediment Concentrations in 1 L sample.
(a) = Edwards Aquifer Authority, unpublished.
(b) = Edwards Aquifer Research and Data Center, unpublished.

Summary of water quality variables measured during storm event 12.

Time [CST] [MM/DD/YYYY HH:MM:SS]	Sample	Discharge [m3/s]	TSS [mg/L]	VSS [mg/L]	NVSS [mg/L]	TN [µg/L]	TP [µg/L]	NH_4^+-N [µg/L]	SRP [µg/L]	NO_3^--N [µg/L]	Turbidity (NTU) (b)	*E. coli* (MPN/ 100mL)
9/7/2018 5:06	1	0.79	788.95	178.30	610.65	3986.88	1552.91	109.23	61.76	733.65	257.06	120958.5
9/7/2018 5:06	1LD	0.79										120958.5
9/7/2018 5:09	2	1.07	554.76	134.75	420.00	3444.60	1034.17	67.99	91.37	992.55	284.13	40820
9/7/2018 5:09	2LD	1.07	564.02	123.81	440.21	4438.86	1000.08	76.28	86.72	964.33	284.13	
9/7/2018 5:12	3	1.12	286.79	60.02	226.77	2564.42	591.12	88.19	98.60	1067.21	178.61	8035
9/7/2018 5:15	4	1.27	240.90	57.08	183.82	2001.72	452.86	76.92	92.40	786.25	110.16	5560
9/7/2018 5:18	5	1.33	172.03	41.35	130.68	2346.86	409.40	133.69	100.66	942.60	102.55	5595
9/7/2018 5:21	6	1.30	154.28	30.22	124.06	1834.07	390.07	77.55	99.12	797.09	103.64	7105
9/7/2018 5:26	7	1.05	145.29	34.84	110.44	1638.10	379.05	52.04	107.03	558.38	86.56	34335
9/7/2018 5:31	8	0.85	159.97	34.97	125.00	1918.54	406.91	68.84	132.68	790.98	78.04	9780
9/7/2018 5:36	9	0.40	169.33	41.75	127.58	1941.36	387.57	58.84	121.84	725.73	91.02	18270
9/7/2018 5:41	10	0.34	90.47	19.52	70.95	1487.69	312.72	35.24	115.64	632.15	70.32	14935
9/7/2018 5:41	10LD	0.34										13010
9/7/2018 5:46	11	0.26	60.77	15.94	44.83	1384.36	270.31	59.48	120.63	621.92	48.74	19365
9/7/2018 5:51	12	0.21	46.23	14.78	31.44	1339.76	245.57	76.92	119.95	651.57	38.62	17240
9/7/2018 5:51	12LD	0.21	47.74	16.43	31.31	1338.33	243.49	64.80	127.00	665.77	38.62	
9/7/2018 6:01	13	0.10	30.79	10.13	20.65	1366.27	213.55	86.27	115.47	680.95	28.93	23055
9/7/2018 6:11	14	0.05	22.80	8.71	14.09	1378.20	200.04	107.11	110.31	822.23	22.66	19365
9/7/2018 6:21	15	0.05	16.93	7.58	9.35	1371.65	200.04	163.03	110.65	891.49	20.06	11795
9/7/2018 6:31	16	0.05	17.24	8.14	9.10	1524.65	182.57	101.16	108.24	909.70	18.28	9590
9/7/2018 6:41	17	0.04	15.50	7.68	7.82	1512.39	180.70	217.25	107.38	931.82	19.76	14255
9/7/2018 6:51	18	0.03	14.64	7.72	6.92	1410.61	160.74	69.69	94.12	984.63	18.99	11235
9/7/2018 7:21	19	0.02	12.00	7.10	4.90	1597.64	148.27	324.83	87.93	1109.84	16.70	7195

9/7/2018 7:51	20	0.01	8.95	6.22	2.73	1610.74	116.67	453.47	71.74	1274.66	13.40	7250
9/7/2018 7:51	20LD	0.01										6770
9/7/2018 8:21	21	0.01	6.36	5.20	1.16	1673.56	104.40	800.04	57.46	1347.39	10.15	5095
9/7/2018 8:21	21FD	0.01	4.66	3.69	0.97	1798.74	105.23	431.35	74.33	1471.73	10.15	5955
9/7/2018 8:21	21FD -SSC	0.01	4.41	3.35	1.06							
9/7/2018 8:51	22	0.00	4.73	4.00	0.73	1678.09	70.72	1010.53	42.99	1534.33	7.23	5810
9/7/2018 9:21	23	0.01	2.51	3.29	-0.78	1701.69	54.92	1138.95	36.63	1648.60	4.87	3560
9/7/2018 9:51	24	0.02	2.10	3.07	-0.97	1816.05	31.63	1412.38	31.12	1700.81	2.79	2120

LD = Lab duplicate
FD = Field duplicate
SSC = Suspended Sediment Concentrations in 1 L sample.
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