# MODELING SEDIMENT YIELD IN THE SINK CREEK

# AND PURGATORY CREEK WATERSHEDS

# NEAR SAN MARCOS, TEXAS

by

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## ABSTRACT

Central Texas, along the Balcones escarpment, experiences high-magnitude precipitation events that have the ability to generate large amounts of runoff. In the past, such events have led to significant urban flooding and have devastated entire communities. In an effort to lessen the severity of such flood events, the city of San Marcos, Texas, with the National Resource Conservation Service, constructed five flood control dams. These dams, located in the headwaters of the San Marcos River, as well as one of its tributaries, have been successful in protecting the city from catastrophic flood events. Due to an increase in urbanization in the region, rainfall runoff modeling has been suggested in order to better understand the hydrologic processes occurring in these watersheds. This study used the Soil and Water Assessment Tool (SWAT) to model and compare sediment yield for Sink Creek and Purgatory Creek watersheds. This comparison allows a better understanding of which variables are more important to soil erosion. Results show that Sink Creek watershed has a higher total sediment yield (t), while Purgatory Creek watershed has a higher specific sediment yield (t/ha). Soil type and land use were found to be the best predictors of erosion. Results also showed that the top 25 percent of the highest total monthly precipitation produced greater than 55 percent of the overall sediment yield during the period of observation.

# 1. INTRODUCTION

In the summer of 1981, 1,800 San Marcos, TX residents were evacuated following major urban flooding. This event led decision makers to approve the construction of five flood control dams in the Sink Creek and Purgatory Creek watersheds to protect the city from future flooding (Earl and Wood 2002). Since the construction of these dams, a disruption in the sediment budget has been quantified downstream in the San Marcos River (Earl and Wood 2002). However, to better understand the sediment budget for these watersheds, more detailed modeling has been suggested (Sansom and Xia 2010).

The purpose of this research was to model and compare sediment yield in both the Sink Creek and Purgatory Creek watersheds. This was accomplished by using the Soil and Water Assessment Tool (SWAT). My research examined the relationships between monthly modeled sediment yield, land use, topography, and precipitation. The purpose of which is to better understand how sediment contributions vary between these two watersheds of the Upper San Marcos River. Specifically, my research addressed the following two questions:

1) Is there a difference in modeled sediment yield between Purgatory Creek watershed at Dam Number 5 and Sink Creek watershed at Dam Number 3 near San Marcos, Texas?

2) If differences exist, how do they relate to land use, topography, and precipitation?

# 2. LITERATURE REVIEW

## 2.1. Geomorphology of Central Texas

A widely accepted idea in geomorphology is that most geomorphically effective regions are those that have a balance between the magnitude and frequency of precipitation events (Wolman and Miller 1960). An exception to that general rule occurs in central Texas, along the Balcones Escarpment. This region is plagued by high-magnitude precipitation events that produce more geomorphically significant floods than anywhere else in the U.S. (Leopold et al. 1964; Patton and Baker 1976; Baker 1977; Caran and Baker 1986). An area known to have thin soils (Cooke et al. 2003), steep slopes, and locally heavy rains (Beard 1975; Baker 1977) gives central Texas the capacity to move large quantities of sediment (Baker 1977; Heitmuller and Asquith 2008). This sediment is eroded off of the steep hillslopes and carried to depositional zones of accumulation (Horton 1945 p316). The sediment then accumulates until the next major precipitation event causes a flood where the sediment can be entrained and transported further down the hillslope to a tributary, eventually reaching the main channel of a stream (Schumm 1960). Within a given stream channel anthropogenic structures, such as dams, may disrupt the natural movement of the sediment by reducing entrainment and storing the sediment behind the dam (Poff et al. 1997; Wohl 2006).

## 2.2. Sediment transport from overland flow

In the study area, high-magnitude precipitation events have the ability to create a large amount of runoff with minimal infiltration. This process of overland flow has been shown to erode and carry sediment from hillsides to zones of accumulation (Horton 1945 p316). Predicting overland flow based sediment transport using empirical derived formulas has been shown to be dependent on velocity, shear stress, and site-specific conditions (Julien and Simons 1984). While multiple types of overland flow may occur, low flow intensities are the most difficult to predict soil erosion potential (Demirci and Karaburun 2012). In contrast, this study will look at sediment yield driven by low-frequency, high-magnitude events in a physiographic setting that produces large volumes of runoff and soil erosion potential (Baker 1977; Verstraeten and Poesen 2000).

### 2.3. Estimating dam reservoir sediment accumulation

Sedimentation accumulation rates varying greatly across watersheds due to drainage density, climate, soil type, slope, and land use (Poff and Hart 2002). Regardless of these complex factors, only one foundational equation (along with its derivatives) has been primarily used in the U.S. for estimating sediment accumulation for the past 70 years. In its simplest form, this equation is calculated by determining the ratio of reservoir sediment capacity (volume) and the sediment inflow (volume/year), commonly known as trap efficiency or TE (Brown 1943; Brune 1953).  Used as a primary means of predicting a given reservoir's useful life, determining the TE became a requirement for dams built after 1960 (Morris and Fan 1998; Poff and Hart 2002). Researchers have since found that the formula underestimates sediment accumulation in large watersheds (Espinosa-Villegas et al. 2009), while overestimating sedimentation rates in smaller watersheds (Rausch and Heinemann 1975).

With the uncertainty of using TE calculations for small watersheds, alternative means exist to measure for long term sediment accumulation behind dams (Romero-Diaz et al. 2007; Castillo et al. 2007; Boix-Fayos et al. 2008; Diaz et al. 2014). These measurements have primarily taken place on small watersheds with check dams. Check dams are strategically placed on an intermediate or ephemeral stream to be used as a means of controlling sediment runoff from hillslopes (Romero-Diaz et al. 2007). These field measuring techniques include: sediment core sampling (Straub et al. 2006), digging trenches to observe stratigraphy (Bussi et al. 2013), geometric calculations from field measurements (Romero-Diaz et al. 2007; Castillo et al. 2007), and topographical surveys (Hooke and Mant 2000; Diaz et al. 2014) (Table 2.1). Topographical surveys are created in the field by collecting elevation points using Global Positioning Systems (GPS). These surveys can be converted to DEMs and compared to historical surveys that were conducted before the construction of the dam (Hooke and Mant 2000).

**Table 2.1. Methods and Purpose to Measure Sediment Volume.**

| Study | Technique to Determine Volume | Purpose of Study |
|---|---|---|
| Hooke and Mant 2000 | Land surveying- DEM. | Monitor change in channel shape following flood event. |
| Straub et al. 2006 | Transect coring in a reservoir. | Determine sediment thickness in a reservoir. |
| Romero-Diaz et al. 2007 | Wedge-pyramid with a trapezoidal base in a horizontal position. | Used as a model validation measurement at a check dam. |
| Castillo et al. 2007 | Wedge- trapezoidal base-multiple cross sections. | Used as a model validation measurement at a check dam. |
| Bussi et al. 2013 | Trench/wedge/textural analysis. | Measure volume of sediment trapped by check dams. |
| Rodriguez-Blanco et al. 2013 | Measured suspended sediment with a differential pressure transducer sensor. | Measure suspended sediment after a storm event. |
| Diaz et al. 2014 | Detailed topographic survey. | Compare technique against Castillo et al. 2007 and Romero et al. 2007. |

**2.4. Estimating erosion using empirical equations**

Empirical equations can be used to estimate soil erosion from a hillslope. A popular empirical equation used to predict soil loss is the U.S. Department of Agriculture's (USDA) Universal Soil Loss Equation (USLE) along with the updated Revised Universal Soil Loss Equation (RUSLE) and Modified Universal Soil Loss Equation (MUSLE) (Wischmeier and Smith 1960; Williams 1975; Renard et al. 1997). These equations use climate, soil, topography, and land use to determine erosion occurring in a given area. The MUSLE is slightly different from the other two equations in that it uses a runoff function to determine erosion. The advantage to the MUSLE is its ability to determine sediment yield from single storm events (Zhang et al. 2009). The USLE and RUSLE do not estimate sediment yield. Rather, they predict annual erosion by using rainfall energy (Zhang et al. 2009). The RUSLE is simply an updated version of the USLE, with updated algorithms that allows it to be applied on a greater number of landscapes. When applied to the watershed scale, it has been found that the RUSLE overestimates sediment erosion rates by neglecting to fully account for sediment traps such as rills, gullies, and other geomorphologic features (Romero-Diaz et al. 2007). Improved algorithms applied in a 44.9 $km^2$ watershed to account for such complex geomorphic features correlated well ($R^2$=0.73) with field observations (Zhang et al. 2013). A drawback to using such algorithms to model complex landscapes in the RUSLE, is the need for high spatial resolution (<5m) DEMs which are often not widely available for use (Zhang et al. 2013). Aside from the lack of high spatial resolution DEMs, the MUSLE, as a standalone equation, has shown to be inconsistent when applied in a study area with high-magnitude, low-frequency soil loss events (Furl et al. 2015). In an area where half of the observed soil loss occurred in the upper 10% of events, the MUSLE was inconsistent with observable measurements (Furl et al. 2015). These inconsistencies are due to USLE derived models to overestimate low erosion values and underestimate high erosion values (Nearing 1998; Furl et al. 2015).

### 2.5. Estimating sediment yield using process-based modeling

There are several process-based models available for modeling sediment yield, runoff, and erosion. Choosing the best model depends on availability of data, scope of the project, or size of the project. Hydrologic models such as SWAT, Water Erosion Prediction Project (WEPP) and its GIS component GeoWEPP have been successful in a wide range of applications. While I chose to use SWAT for this project, I will provide an explanation on WEPP and GeoWEPP here to justify my selection of SWAT.

The Water Erosion Prediction Project (WEPP) is a process-based model that was developed to determine net soil loss both spatially and temporally (Nearing et al. 1989). Fundamentals of stochastic weather generation, infiltration processes, hydrology, soil physics, plant science, hydraulics, and erosion mechanics are the drivers for the model (Flanagan and Livingston 1995). Due to the model's process-based logic, it can be used in multiple climate and topographical conditions (Nearing et al 1989). One of the major differences between the RUSLE and the WEPP is the WEPP's ability to differentiate between high and low magnitude precipitation events. Its ability to differentiate these events is a major reason why the WEPP model has been determined as a more appropriate model to measure net sediment yields (Laflen et al. 1997).

Incorporating the WEPP model into a GIS environment, rather than its native desktop version, has been shown to save data processing time and allow for modifications to the input variables (Cochrane and Flanagan 1999). The GeoWEPP extension for Environmental Systems Research Institute's (ESRI) ArcMap program was the first GIS tool developed to be used in conjunction with the WEPP model desktop version (Renschler 2003). This extension allows the WEPP model data inputs to be used in a GIS environment and allows ArcMap users to customize DEM inputs and land use scenarios (Renschler 2003). The GeoWEPP extension is a vital tool in modeling areas >5 ha (the WEPP's original max area) due to its ability to divide a larger watershed into user defined smaller hillslopes (Renschler 2003). The Topography Parameterization algorithm (TOPAZ) is used in combination with the DEM, user specified critical source area (CSA), and the minimum source channel length (MSCL) (Garbrecht and Martz 1997). These results then determine the stream channels and hillslope size to be modeled for the study area. Climate data estimates for the GeoWEPP model are generated from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) (Daly et al. 1997). The PRISM database contains average monthly precipitation values, as well as average elevations for a 2.5-minute grid. Precipitation data were developed by interpolating and extrapolating precipitation amounts between weather stations (Daly et al. 1997). Within the GeoWEPP model, custom PRISM files can be imported, existing PRISM data can be modified, or the default CLIGEN precipitation data can be accepted (Daly et al. 1997).

The CLIGEN model is the native climate generator for the WEPP model and can be used instead of the PRISM model in the GeoWEPP extension. One advantage to the

CLIGEN model is its ability to generate (a modeled) 100 years' worth of weather data for a given area. The CLIGEN model is a stochastic weather model that can model the needed precipitation events to run the WEPP model (Meyer 2016).

Limitations of the GeoWEPP model apply in very large watersheds (>500 $mi^2$) where the GeoWEPP model overestimates sediment yield (Maalim et al. 2013) (Table 2.2), as well as raster cell limitations (>200,000) limiting the input to the model. The sizes of the watersheds in this study fall well within the appropriate range of application for the GeoWEPP. However, due the spatial resolution of the DEMs (10m) the number of cells surpasses the limit of recommend for model application (Xiong et al. 2014). This shortcoming, along with the tedious and non-transparent means to create custom (non-simulated) weather inputs, makes it difficult to model the study area with the WEPP or GeoWEPP models.

**Table 2.2. Results from Studies That Have Used the WEPP and GeoWEPP Models.**

| **Study** | **Size of Study Area** | **Modeled Used** | **Modeled Sed. Yield** | **Measured Sed. Yield** |
|---|---|---|---|---|
| Pandey et al. 2008 | 11 $mi^2$ | WEPP | 2.48 t $ha^{-1}$ $yr^{-1}$ | 2.69 t $ha^{-1}$ $yr^{-1}$ |
| Yuksel et al. 2008 | 490 ha | GeoWEPP | 6.95 t $ha^{-1}$ $yr^{-1}$ | 5.48 t $ha^{-1}$ $yr^{-1}$ |
| Yu et al. 2009 | 28 $mi^2$ | GeoWEPP | 6.01 t $ha^{-1}$ $yr^{-1}$ | 7.35 t $ha^{-1}$ $yr^{-1}$ |
| Maalim et al. 2013 | 1112 $mi^2$ | GeoWEPP | 589,400 t/yr * | 224,900 t/yr * |
| Pieri et al. 2014 | 192 ha | GeoWEPP | 32.5 t $ha^{-1}$ $yr^{-1}$ | 37.5 t $ha^{-1}$ $yr^{-1}$ |

* Measured in TSS

The Soil and Water Assessment Tool (SWAT) is a process-based, conceptual, continuous time, hydrologic model created to help managers better understand impacts on water supply originating from non-point source pollution (Arnold et al. 1998). Developed to be applied in ungauged watersheds (Arnold et al. 1998; Chaubey et al. 2010), SWAT is capable of accurately modeling both small (Gitau et al. 2008) and large areas (Green et al. 2006). Temporally, SWAT is capable of modeling a range of steps from daily to yearly (Renschler and Lee 2005; Heathman et al. 2009).

The hydrologic cycle, climate, and land management are the major components of SWAT (Chaubey et al. 2010). SWAT is capable of breaking apart a large watershed into sub-watersheds, which the user can define the size. Sub-watersheds can further be divided into hydrologic response units (HRUs), which are characterized by similar land use, land management, soil type, and slope. Parameters for each HRU can then be modified to develop a true description of processes occurring within the watershed (Chaubey et al. 2010). Watershed outlet points, a point where SWAT will measure modeled hydrologic parameters, can added to any stream location in the watershed. The ability to customize a robust range of parameters in a study area makes SWAT a popular option to model water runoff, sediment yield, and management scenarios. For this reason, there have been multiple versions of SWAT, with each version increasing the options to customize the inputs of the model.

Another major advantage to SWAT is that it allows the user an option to setup and run the model in a geographic information system (GIS) environment, as opposed to its native executable files. ArcSWAT allows the user to delineate a watershed, input soil and land use data, modify data inputs, create/modify HRUs, and execute the SWAT model itself. Minimum inputs for ArcSWAT include, a digital elevation model (DEM), land use data, and soil data. Climate data including precipitation, temperature, solar radiation, relative humidity, and wind can also be used. If such data is not available, the parameters can be simulated using climate normal datasets available with SWAT. There are many other hydrologic parameters that the user can customize in order to tailor the model to their study area, or research question. When SWAT is executed, the results are stored in a project database. SWATeditor, a data editing tool developed to complement ArcSWAT, can then be used to access the database. SWATeditor is capable of conducting sensitivity analysis, autocalibration, and uncertainty analysis on results from ArcSWAT.

SWAT has been shown to perform well when modeling sediment yield at both the daily and monthly time steps (Table 2.3) (Santhi et al. 2001; Saleh and Du 2004; Betrie et al. 2011; Oeurng et al. 2011). Choosing the correct DEM resolution to model sediment yield is imperative when using SWAT. Prediction errors for sediment yield have been found to occur when a DEM larger than 50m is used (Chaplot 2005). A coarser resolution DEM may fail to account for some elevation changes where sediment deposition or accumulation may occur. Correctly choosing the number of sub-watersheds is another key component of accurately predicting sediment yield. The area of each sub-watershed should equal approximately 3 percent of the entire study area (Jha et al. 2004; Migliaccio and Chaubey 2008). Areas less than 3 percent have very little effects on SWAT's algorithms pertaining to sediment deposition and degradation (Jha et al. 2004). This is due to a threshold of the length and slope factor (LS) in the Modified Universal Soil Loss Equation (MUSLE). Increasing the sub-watersheds can significantly change the LS factor and potentially skew model results.

**Table 2.3. Nash-Sutcliffe Values for SWAT Studies Modeling Sediment Yield.**

| Study | Size of Study Area | NS- Monthly | NS-Daily |
|---|---|---|---|
| Santhi et al. 2001 | 2657 $mi^2$ | 0.70/0.23* | N/A |
| Saleh and Du 2004 | 904 $mi^2$ | 0.59 | -3.51 |
| Betrie et al. 2011 | 114680 $mi^2$ | 0.88 | 0.83 |
| Oeurng et al. 2011 | 690 $mi^2$ | N/A | 0.31 |

Note: NA= not available
*Study observed two different watersheds. The first value is Hico, the second value is Valley Mills.

Although SWAT has not been applied in the Purgatory or Sink Creek watersheds, there has been a SWAT application nearby on the Upper Guadalupe River (Bumgarner and Thompson 2012). Even though the purpose of that study was to model brush management practices, its calibrated parameters may be helpful in calibration of SWAT for this research. As customary with most literature of SWAT applications, calibrated parameters and their original values are provided (Santhi et al. 2001; Oeurng et al. 2011; Betrie et al. 2011; Bumgarner and Thompson 2012; Zettam et al. 2017).

After an initial SWAT simulation is completed, it is very likely that the results do not accurately reflect the observed data. Therefore, the input parameters need to be modified in order for the results to better represent processes occurring within the watershed. Calibrating SWAT to measured flow data is the first step in fitting the model to the watershed. One option to calibrate SWAT is to identify the sensitive input parameters. This can be done by expert judgement, or by conducting a local or global sensitivity analysis (Arnold et al. 2012). A local sensitivity analysis will identify sensitive parameters by changing one at a time. While a global sensitivity analysis requires multiple simulations, allowing all of the parameter values to change (Arnold et al. 2012). However, a sensitivity analysis is not always necessary as manual calibration methods have been developed for SWAT (Arnold et al. 2012). It is during the calibration process that the user modifies sensitive parameters in order to better represent the measured values. Validation is the final step of the process and ensures SWAT is capable of making sufficiently accurate simulations (Arnold et al. 2012). It is during validation that the calibrated parameters are modeled and compared to observed data not used in the calibration. Sensitivity analysis, calibration, and validation can be completed using a variety of programs in SWAT-CUP (Abbaspour et al. 2007).

When parameter data (e.g. discharge, sediment) is available, different methods in developing and applying regional parameters to ungauged watersheds have been successful using SWAT (Heuvelmans et al. 2006; Gitau and Chaubey 2010; Sellami 2014). A widely-used regionalization method, regression-based parameters (Razavi and Coulibaly 2013), has yielded adequate results when using calibrated parameters from SWAT on ungauged watersheds (Gitau and Chaubey 2010). It is important that the ungauged watershed share key physical characteristics with watersheds from which the regional parameters were derived. The most important of the watershed physical characteristics includes the area, average slope, dominant land use, and soil type (Heuvelmans 2006).

Determining which model parameters to apply to the ungauged watershed can vary depending on the outcome of the sensitivity analysis, calibration, and validation of the SWAT model (Arnold et al. 2012). Some have used as many as 16 parameters (Gitau and Chaubey 2010), others have used formulas to remove the subjectivity from choosing the parameters (Sellami et al. 2014). While some simply use all of the calibrated parameters to keep the integrity of the model (Heuvelmans et al. 2004).

Due to a lack of continuous sediment measurements in the region of the study area, applying a regionalization method is not feasible. However, downstream from the study area there are gauges with long periods of discharge measurements. Calibrating SWAT to a gauge downstream from the study area using discharge as a single parameter may increase the validity of modeled sediment yield results at the Dam No. 3 and Dam No. 5.

**2.6. Research significance**

Understanding the effects these dams have on flood events in the San Marcos River has been studied by Earl and Wood (2002), but there is still more to understand. The relationship of increasing urbanization and sediment yield has also been modeled for the study area (Sansom and Xia 2010). This relationship is not as well understood, as modeled results indicated a decrease in sediment yield with an increase in urbanization (Sansom and Xia 2010). These results contradict field collected data in the San Marcos River (Wood and Gilmer 1996). This difference is attributed to the model's limited capabilities to accurately account for sediment runoff from construction sites. As well as the observation that urbanization is occurring in areas with thin soils that don't contribute a significant amount of sediment to the stream (Sansom and Xia 2010).

What has not been studied in detail is the difference in sediment yield between these two watersheds and its relationship with basin characteristics and precipitation. On account of increasing urbanization, especially in the Purgatory Creek watershed, having a better understanding of sediment yield is important to city planners and mangers. Accurate estimates of sediment yield can inform water and sediment storage-related maintenance needs for these dams. Sediment accumulation behind these dams might lead to a loss in storage capacity, and/or damage to low level grates and water outlets (TCEQ 2016). The result of such sediment accumulation could lead to dam failure (TCEQ 2016). With the main purpose of these dams being flood control, a loss in storage capacity could potentially cause these structures to perform insufficiently during major flood events.

A complete understanding of sediment supply and transport in the study area's region is an ongoing challenge due to its unique terrain and climatic events (Leopold et al. 1964; Baker 1977; Heitmuller and Asquith 2008). This research presents a smaller scale study of sediment yield in a region of growing population, where others have suggested such research should occur (Sansom and Xia 2010). Due to continuing improvements in GIS technology and model development, reasonably accurate assessments of sediment yield from these two watersheds can be estimated and compared. These methods created for this study to model sediment yield may be applicable in watersheds with similar physiographic and climatic characteristics.

## 3. METHODS

### 3.1. Study area

The study area for this research includes two watersheds in northern Comal and south-central Hays Counties near San Marcos, TX (Figure 3.1). The two watersheds are the Sink Creek and Purgatory Creek watersheds. Sink Creek represents the headwaters of the San Marcos, River, while Purgatory Creek is a tributary of the San Marcos River located approximately 0.65 miles downstream from Spring Lake.

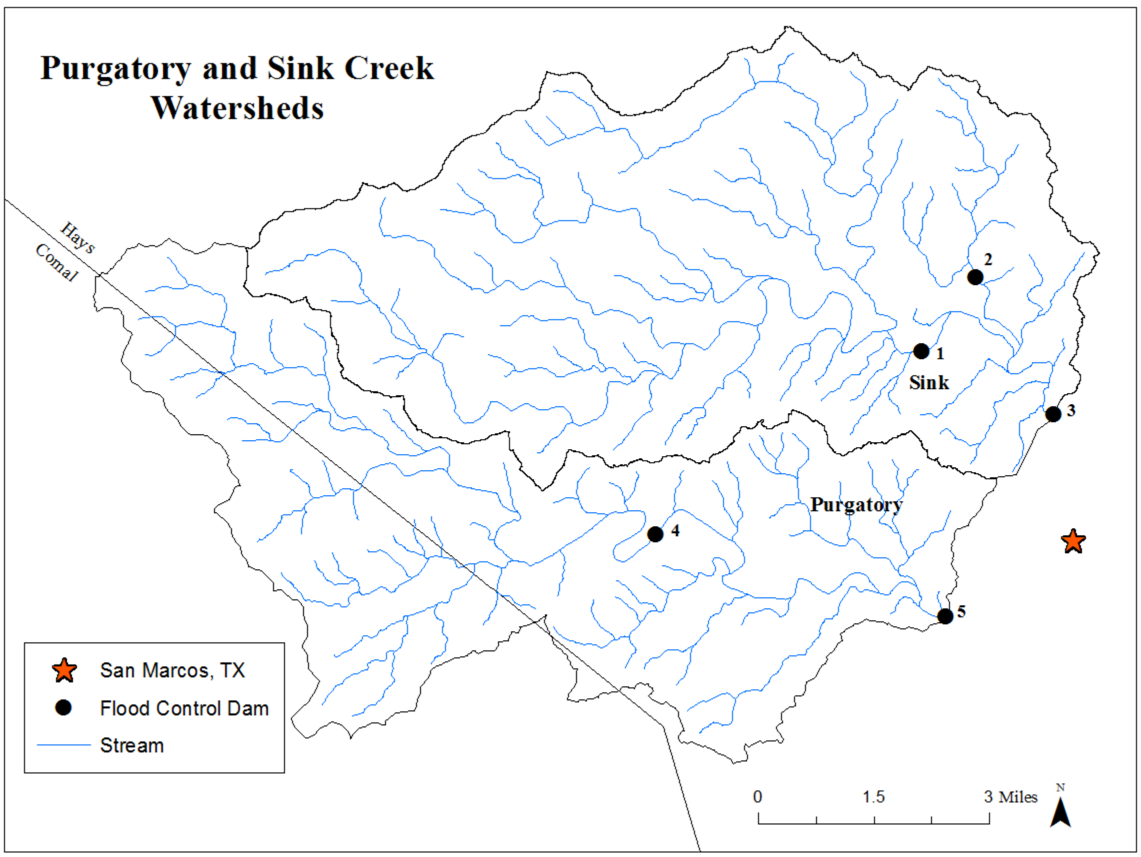



**Figure 3.1.** Study Area with Locations of Flood Control Dams.

The study area did not include the entire Sink Creek and Purgatory Creek watersheds. Instead, the study area included the upstream portions of the watersheds from the furthest downstream flood control dams. Dam site number 5 is located on Purgatory Creek within the Purgatory Creek Park recreation area. Dam site number 3 is located on Sink Creek, on private property. Both watersheds have additional upstream flood control dams. Purgatory Creek has one additional dam, while Sink Creek has two additional dams (Figure 3.1). The sizes of the watersheds are similar, with Purgatory Creek watershed encompassing 34 $mi^2$ while Sink Creek watershed is 43 $mi^2$. Both watersheds cover primarily rural rangeland, with the exception of Purgatory Creek's covering a sizeable urban subdivision. The amount of subdivisions will most likely increase in the study area as Hays County's population is expected to increase by 400% (SMWI 2017). The main soil type in both watersheds is Comfort-Rumple Eckrant (Batte et al.1984) underlain by Cretaceous Edwards Limestone.

The dams in this study are not categorized as check dams, although they share some of the same characteristics. The most important of these characteristics is the location of these dams being on intermittent and ephemeral streams. Sink Creek and Purgatory Creek are heavily influenced by intense low-frequency, high-magnitude precipitation events and can experience high flows following such events. These high-magnitude events can fill the reservoirs with runoff very quickly. Subsequently, the water drains out of the reservoirs at a rapid rate as surface water and infiltrating the ground water. This phenomenon makes it difficult for sediment to be deposited behind the dam.

### 3.2. Data

All of the data used in this study, its source, and format are outlined in Table 3.1. Specifically, data inputs for the SWAT model included a 2013 10m DEM, the 2011

National Land Cover Dataset (NLCD), and the 2012 Soil Survey Geographic Database. Weather inputs for the SWAT model came from the Climate Forecast System Reanalysis (CFSR) (Dile and Srinivasan 2014). Daily weather values from five weather stations from January 1990 to December 2010 were used. All of the spatial data were projected using NAD 1983 (2011) State Plane Texas South Central projection (WKID 103156).

**Table 3.1. Data Type, Source, and Format.**

| Data Type | Data Source | Data Format |
|---|---|---|
| Digital Elevation Model | 2013 National Elevation Dataset | Raster 10m x 10m |
| Land Cover | 2011 National Land Cover Dataset | Raster 30m x 30m |
| Soil | 2012 Soil Survey Geographic Database | GIS Vector |
| Discharge | USGS Stream Gauge 08172000 San Marcos River at Luling, TX- 1990 to 2010 | CSV |
| Weather | 1990-2010 Climate Forecast System Reanalysis (5 stations) | Text Files |
| Streams | National Hydrography Dataset (NHD) | GIS Vector |

### 3.3. Quantifying basin characteristics

In order to compare the two watersheds for this study, certain basin characteristics were quantified. The first of which was land use and landcover. Due to certain land use and landcover resulting in greater erosion rates, the 2011 NLCD was used to calculate a percentage of each land use type for both watersheds.

The basin relief ratio and the drainage density for each watershed were also calculated. The basin relief ratio (*Rh*) is calculated where *H* is the difference of the highest and lowest point in the watershed and *L* is the length of watershed parallel with the main stream.

$$Rh = H/L \tag{1}$$

Drainage density for each watershed was measured with the drainage density equation: where $D_d$ is equal to the drainage area, sum$L$ is equal to the total length of streams and $A$ is equal to the area of the watershed. The length of streams was derived from the National Hydrology Dataset (NHD).

$$D_d = \frac{sumL}{A} \tag{2}$$

### 3.4. SWAT model

A SWAT model was created with the outlet at U.S. Geological Survey (USGS) stream gauge 08172000, San Marcos River at Luling, Texas (Figure 3.2). The model was ran from 1990 to 2010 (21 years) with measured precipitation and temperature data from 5 climate stations. Following a 5-year warm up period, the model generated hydrologic outputs for years of 1995 to 2010 (16 years).

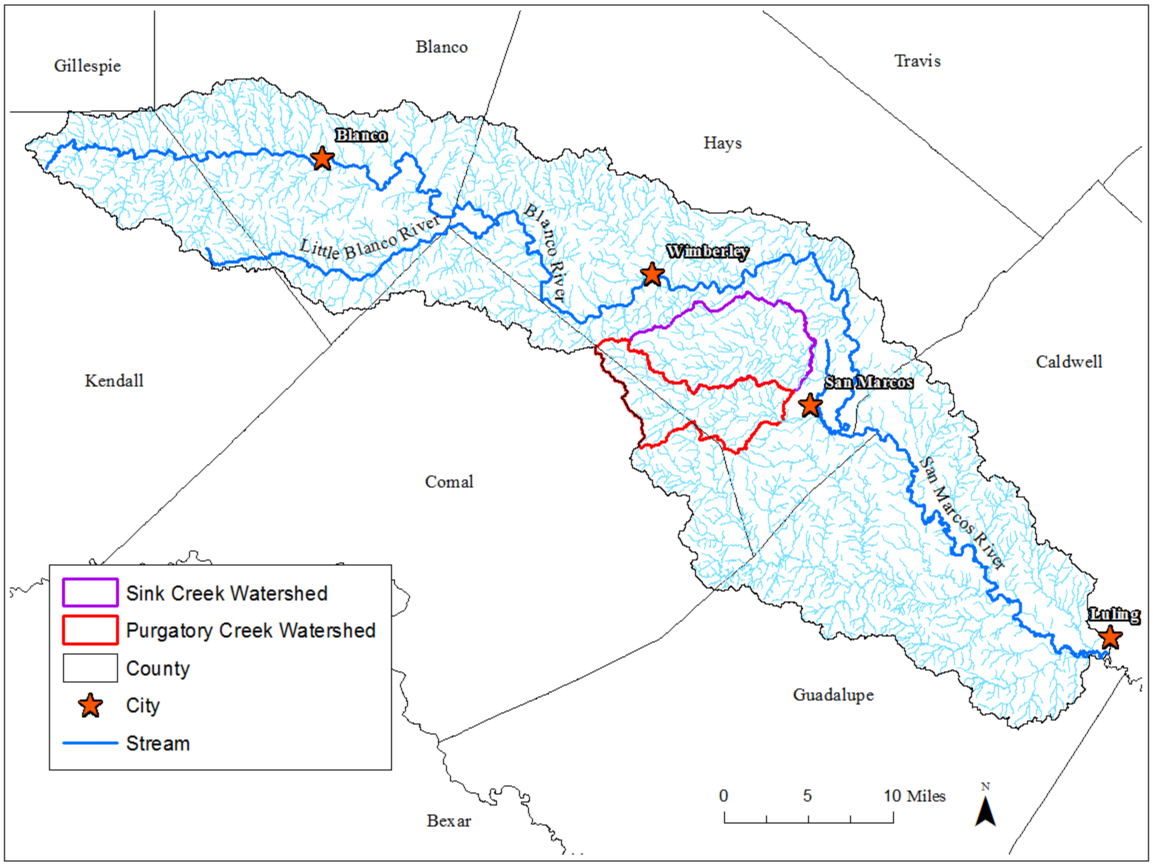



**Figure 3.2.** Watershed Delineated from Stream Gauge 08172000 San Marcos River at Luling, TX.

ArcSWAT was used for preparing data inputs and executing the SWAT model. In order to accurately model sediment yield, the Sink Creek and Purgatory Creek watershed's areas were divided into sub-watersheds no larger than 3 percent of their entire area (Jha et al. 2004; Migliaccio and Chaubey 2008). In comparison, the two watersheds are close in size to an average Hydrologic Unit Code (HUC) 12, which is approximately 40 mi$^2$ (Purgatory Creek watershed is 34 mi$^2$ while Sink Creek watershed is 43 mi$^2$). That means the sub-watersheds for this study are about 3 percent of an average HUC 12 watershed. A total of 178 sub-watersheds were delineated for the entire SWAT model. Specifically, 63 sub-watersheds were delineated in the Purgatory Creek watershed and 78 in the Sink Creek watershed (Figure 3.3). Monitoring points were then added at the outlet of each watershed, dam No. 5 and dam No. 3 respectively. Once the sub-watersheds were created, hydrologic response units (HRUs) were defined using the LCLU, soil, and slope data inputs. Due to the unique topography of the study area, as well as methods used in prior studies in the area, 5 slope classes were used (Bumgarner and Thompson 2012). A total of 1260 HRUs were created for the entire model.

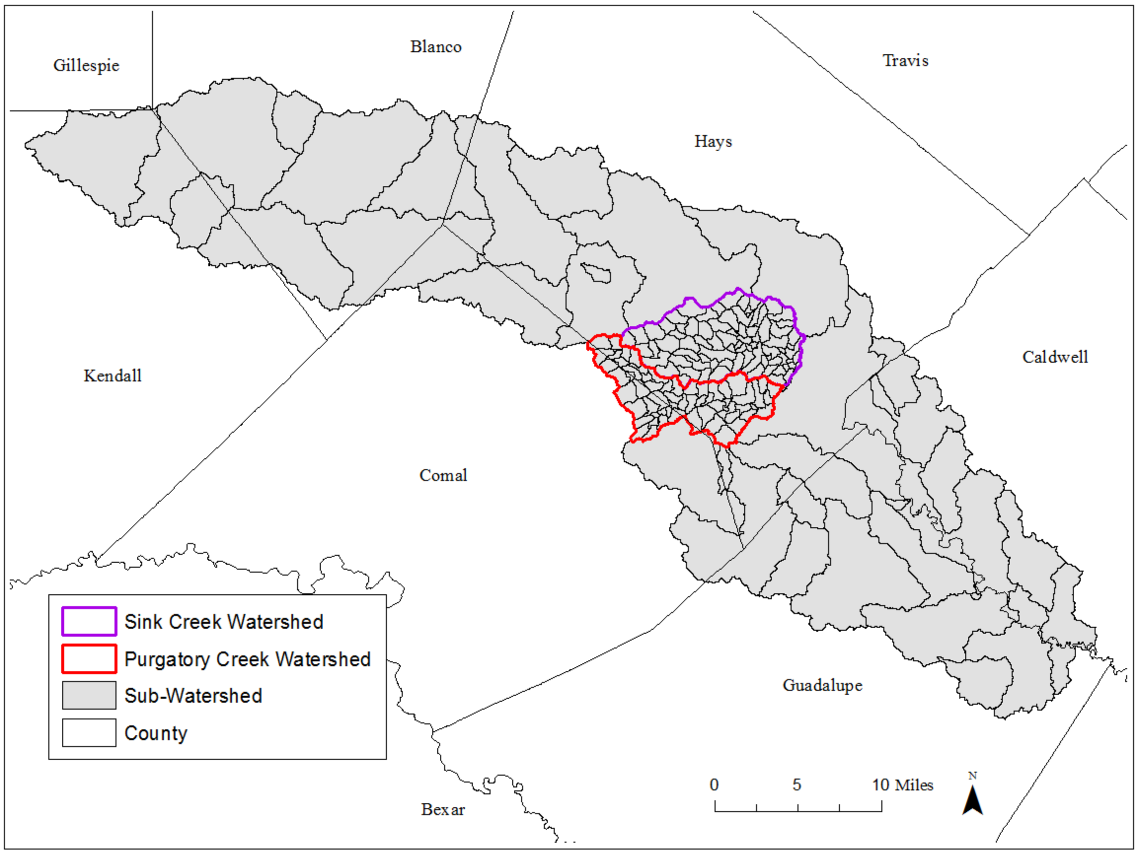



**Figure 3.3.** Sub-Watersheds Delineated for the SWAT Model.

There are many equations SWAT uses to model the hydrology of a watershed. Two in particular were of importance for this study. SWAT uses the water balance equation as a base for the hydrology model:

$$\mathrm{SW_t} = \mathrm{SW} + \sum_{t=1}^{t} (R_i - Q_i - ET_i - P_i - QR_i) \tag{3}$$

where SW is the soil water content, *t* is time in days, *R* is precipitation, *Q* is runoff, *ET* is evapotranspiration, *P* is percolation, and *QR* is return flow; all values are daily and units are in mm (Arnold et al. 1998).

SWAT uses the Modified Universal Soil Loss Equation (MUSLE) to determine sediment yield for each sub-watershed (Arnold et al. 1998). The MUSLE is calculated by:

$$Y = 11.8\left(Vq_p\right)^{0.56} (K)(C)(PE)(LS) \tag{4}$$

where Y is the sub-watershed's sediment yield in t, *V* is sub-watershed surface runoff in $m^3$, $q_p$ is peak flow rate for the sub-watershed in $m^3 \cdot s^{-1}$, *K* is the erodibility factor, *C* is the crop management factor, *PE* is erosion control practice, and *LS* is the length and slope factor (Williams and Berndt 1977; Arnold et al. 1998).

A widely-used method to evaluate SWAT performance is the Nash-Sutcliffe coefficient of model efficiency (*E*) (Nash and Sutcliffe 1970). The *E* is calculated by:

$$E = 1 - \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} (O_i - \bar{O})^2} \tag{5}$$

where *O* are observed values and *P* are predicted values (Krause et al. 2005).

The *E* ranges from negative infinity to 1, with values closer to 1 indicating a better fit between predicted and observed values. Some have found that values of greater than 0.5 for all timesteps as satisfactory for SWAT applications (Gassman et al. 2007). Others have developed a classification system based on monthly values for SWAT. *E* values may be classified as "very good" ($E > 0.75$), "good" ($E \geq 0.65$ & $< 0.75$), "satisfactory" ($E \geq 0.5$ & $< 0.65$), or "unsatisfactory" ($E \leq 0.5$) (Moriasi et al. 2007). This research used *E* values greater than 0.5 at the monthly timestep as acceptable.

The Coefficient of Determination ($R^2$) is another method used to measure modeled performance. It is calculated as:

$$R^2 = \left( \frac{\sum_{i=1}^{n} (O_i - \bar{O})\,(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{n} (O_i - \bar{O})^2}\ \sqrt{\sum_{i=1}^{n} (P_i - \bar{P})^2}} \right)^2 \qquad (6)$$

where *O* are observed values and *P* are predicted values (Krause et al. 2005). The $R^2$ estimates the dispersion of the observed and predicted values with a range of 0 to 1 and can be applied to all timesteps. A value of 0 indicates a lower correlation, while a value of 1 shows equal dispersion between observed and predicted values (Krause et al. 2005).

Due to a lack of measured sediment data for the region, it was impossible to calibrate SWAT to sediment yield for this study. Alternatively, SWAT was calibrated using observed average flow measurements from gauge 08172000 from January 1995 to

December 2002 (8 years). This time range consisted of adequate wet and dry conditions (Figure 3.4), as well as a short overall computing time to run the model. The computing time was important in that multiple simulations of the model needed to be ran for the calibration process. The validation period was also 8 years (January 2003 to December 2010) and like the calibration period, represented an acceptable range of wet and dry conditions. Calibrating SWAT to the flow of the downstream gauge may result in input parameters more representative of the watershed. Which in turn, lowers the uncertainty of the modeled sediment yield. The goal of the flow calibration was to obtain a suitable model performance ($E > 0.5$) at the monthly timestep.

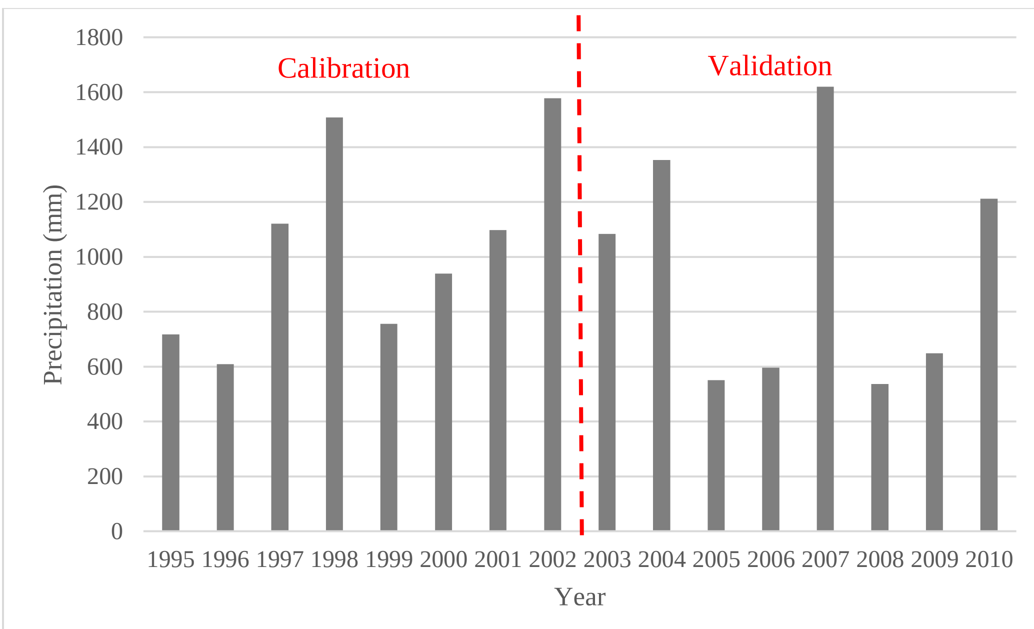



**Figure 3.4**. Yearly Precipitation Totals (mm) for the Calibration and Validation Periods.

The calibration process started with filtering the baseflow from the observed discharge measurements using a program based on techniques described by Arnold and Allen 1999 (Arnold and Allen 1999). These observed flow values were then used in a sequential uncertainty fitting procedure available in SWATs calibration program, SWAT-CUP (Abbaspour et al. 2004, Abbaspour et al. 2007). The calibration program in SWAT-CUP, SUFI-2, was developed to account for uncertainties in the measurement, among other factors, associated with hydrologic observations (Abbaspour et al. 2004). Parameters used to calibrate SWAT to flow were selected based on a nearby SWAT application (Bumgarner and Thompson 2012) as well as previously identified sensitive flow parameters from multiple SWAT applications (Arnold et al. 2012) (Table 3.2).

The SUFI-2 program allows ranges of input values to be set by the user. Where applicable, ranges of parameters were determined by using results from a nearby SWAT application (Bumgarner and Thompson 2012). These ranges were used in 200 simulations with an objective function of Nash-Sutcliffe (*E*) equaling 0.5 at the monthly timestep.

The result of SUFI-2 is not a single set of values, but rather a set of high and low parameters that fit in a 95 percent probability distribution referred to as the 95PPU. The fitted value is the value of a parameter from the simulation that came the closest to achieving the objective function, while staying within the defined parameters (Table 3.3).

**Table 3.2. Original Values and their Description with SUFI-2 Calibrated Fitted Values and New Parameters.**

| Parameter | Description | Original Value | Fitted Value | Min | Max |
|---|---|---|---|---|---|
| v__ALPHA_BF.gw | Baseflow alpha factor (days). | 0.048 | 0.49 | 0.1 | 0.5 |
| v__CANMX.hru | Maximum canopy storage. | 0 | 54.83 | 30 | 60 |
| v__CH_K2.rte | Effective hydraulic conductivity in main channel alluvium. | 0 | 16.89 | 6 | 20 |
| r__CN2.mgt[1] | SCS runoff curve number. | ** | -0.19 | -0.2 | 0.2 |
| v__GW_DELAY.gw | Groundwater delay (days). | 31 | 50.85 | 30 | 90 |
| v__GW_REVAP.gw | Groundwater "revap" coefficient. | 0.02 | 0.12 | 0.05 | 0.15 |
| v__GWQMN.gw | Threshold depth of water in the shallow aquifer required for return flow to occur (mm). | 1000 | 1452.50 | 1000 | 2000 |
| v__RCHRG_DP.gw | Deep aquifer percolation fraction. | 0.05 | 0.33 | 0.1 | 0.8 |
| v__SURLAG.bsn | Surface runoff lag time. | 4 | 3.01 | 1 | 5 |
| v__ESCO.hru | Soil evaporation compensation factor. | 0.95 | 0.73 | 0.6 | 0.85 |
| v__REVAPMN.gw | Threshold depth of water in the shallow aquifer for "revap" to occur (mm). | 750 | 189.50 | 100 | 300 |
| v__EPCO.hru | Plant uptake compensation factor. | 1 | 0.57 | 0.25 | 0.75 |
| r__SOL_AWC.sol | Available water capacity of the soil layer. | ** | 0.27 | -0.2 | 0.4 |

** multiple values
v__ existing parameter is replaced by a given value
r__ existing parameter value is multiplied by 1+ a given value
[1] Uncalibrated mean CN2 = 73.65

SUFI-2 uses two statistics to quantify the goodness of fit between the simulated and observed data in the 95PPU. The *P-factor* is between 0 and 1 and is the percentage of observed data in the 95PPU band. While the *R-factor* ranges from 0 to infinity and is the average width of the band divided by the standard deviation of the observed data. Although no true values exist to determine satisfactory results, values closer to one are considered acceptable (Abbaspour 2004, Abbaspour 2013).

A global sensitivity analysis was conducted during the 200-simulation iteration on both the calibration and validation runs (Table 3.3). Out of the 13 parameters, both the validation and the calibration had four parameters with *P-values* significant at the 95 percent level. Of the four parameters, three were sensitive during both the calibration and validation. These values included the SCS runoff curve number (CN2), available water capacity in the soil layer (SOL_AWC), and the baseflow alpha factor (ALPHA_BF). Only the calibration found the effective hydraulic conductivity in main channel alluvium (CH-K2) to be sensitive, while the validation found maximum canopy storage (CANMAX) as sensitive (Table 3.3).

**Table 3.3. Global Sensitivity Results from SUFI-2 Calibration and Validation.**

| **Calibration** | | | **Validation** | |
|---|---|---|---|---|
| Parameter | *P-value* | | Parameter | *P-value* |
| CN2.mgt | 0.00 | | CN2.mgt | 0.00 |
| SOL_AWC.sol | 0.00 | | SOL_AWC.sol | 0.01 |
| ALPHA_BF.gw | 0.00 | | CANMX.hru | 0.01 |
| CH_K2.rte | 0.05 | | ALPHA_BF.gw | 0.02 |
| ESCO.hru | 0.16 | | CH_K2.rte | 0.06 |
| CANMX.hru | 0.23 | | GW_REVAP.gw | 0.09 |
| GW_DELAY.gw | 0.28 | | ESCO.hru | 0.14 |
| GW_REVAP.gw | 0.33 | | RCHRG_DP.gw | 0.20 |
| SURLAG.bsn | 0.44 | | SURLAG.bsn | 0.44 |
| REVAPMN.gw | 0.56 | | GW_DELAY.gw | 0.65 |
| RCHRG_DP.gw | 0.70 | | REVAPMN.gw | 0.69 |
| GWQMN.gw | 0.77 | | EPCO.hru | 0.74 |
| EPCO.hru | 1.00 | | GWQMN.gw | 0.93 |

The validation process followed calibration using the years 2003 to 2010 (8 years). With the same parameters, as well as the same minimum and maximum values, the SUFI-2 program was again used to run 200 simulations.

# 4. RESULTS

## 4.1. SWAT model flow calibration and validation

Model performance statistical measures from the calibration period using the sequential uncertainty fitting procedure in SWAT-CUP, SUFI-2, were acceptable at the monthly timestep (Table 4.1, Figure 4.2). The SUFI-2 model was given an objective function of Nash-Sutcliffe (*E*) = 0.5 and ran one iteration of 200 simulations. An *E* of 0.55 was determined by SUFI-2 as the best fitted parameters for the objective function. Out of the 200 simulations, 111 met or exceeded excited a *E* = 0.5, with the highest simulation being *E* = 0.77. The Coefficient of Determination, $R^2$ equaled 0.60, out of a range of -1 to 1 (Figure 4.1). The SUFI-2 model performance measures represented by the *P-factor* and the *R-factor* were 0.68 and 1.00, respectively. Both of which fall within acceptable range of the SUFI-2 model performance. The validation period yielded some model performance measures that were less favorable than the calibration period (Table 4.1). Like the calibration process, SUFI-2 was used for one iteration, 200 simulations with an objective function of *E* = 0.5. The same parameters, as well as their minimum and maximum values were used. An *E* of 0.43 was the highest and best result, with zero simulations meeting the objective function. The $R^2$ value was 0.46, while the *P-factor* equaled 0.74, and the *R-factor* equaled 1.07. Both the *P-factor* and *R-factor* showed acceptable performance for the SUFI-2 model.

The SUFI-2 sensitivity analysis found three of the 13 parameters had *P-value'*s less than 0.05 during both the calibration and validation (Table 3.3). The curve number (CN2), as well as the water capacity in the soil layer (SOL_AWC) were the most sensitive in both model runs. Furthermore, these two values were the only two parameters that were calibrated on a percentage change rather than a replaced value (Table 3.2). This technique was implemented due to the multiple values in the HRUs of the study area. For the best fitted parameters run, CN2 dropped 20 percent, while 24 percent was added to the SOL_AWC (Table 3.2). The least sensitive parameters for the SUF-2 model were the threshold depth of water in the shallow aquifer required for return flow to occur (GWQMN) and the plant uptake compensation factor (EPCO).

For both the validation and calibration periods, the model consistently underestimated the flow (Figure 4.2). Conversely, the uncalibrated SWAT model results grossly overestimated the flow. In order to better represent the flow, the curve number was dropped 19 percent during the SUFI-2 model runs. It is interesting to note that some months were better estimators than others. This was most likely caused by weather stations inaccurately measuring total precipitation. Due to the area size and the small amount of weather stations, some rain events may have been over or under reported.

**Table 4.1. Statistical Results from SUFI-2 Calibration and Validation.**

| Statistic | Calibration | Validation |
|---|---|---|
| *P-factor* | 0.68 | 0.74 |
| *R-factor* | 1.00 | 1.07 |
| *E* | 0.55 | 0.43 |
| $R^2$ | 0.60 | 0.46 |

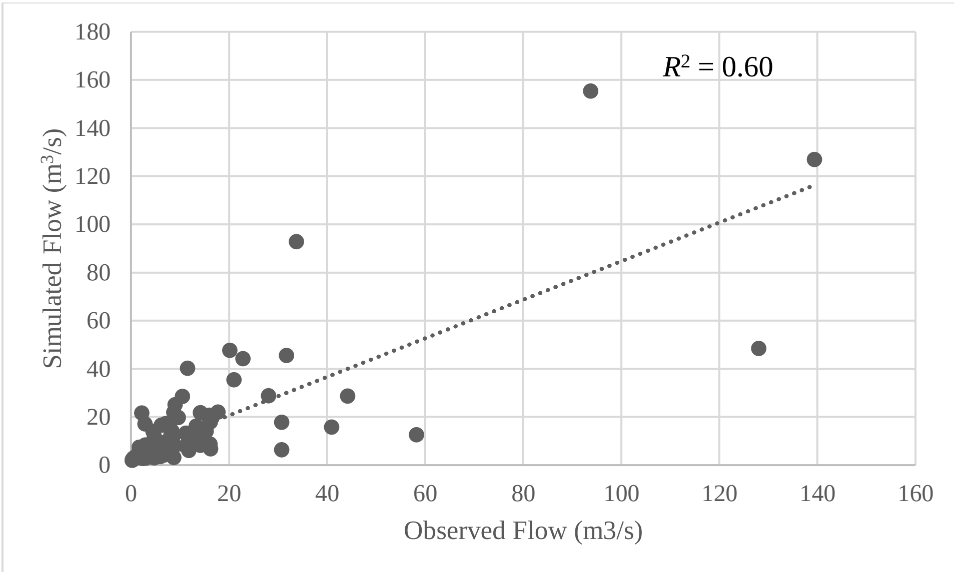



**Figure 4.1.** Monthly Observed vs Simulated Flow for the Calibration Period.

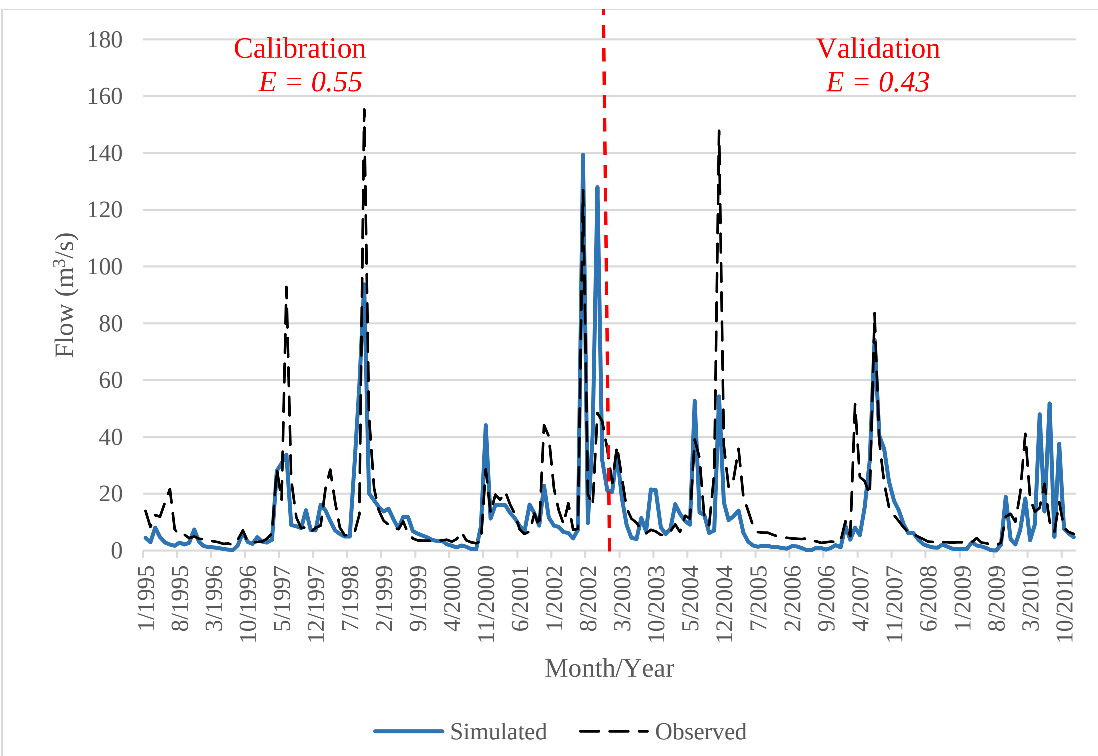



**Figure 4.2.** Hydrograph Monthly Observed and Simulated Flow (m$^3$/s).

### 4.2. SWAT modeled sediment yield

Results of the modeled sediment yield are presented for the calibration period, 1995-2002 and will be referred to as the period of observation for the remainder of this paper. This time period was chosen due to the acceptable model performance measures obtained during calibration to flow (Table 4.1). Yearly and monthly totals, as well as means of sediment yield are presented for both watersheds (Table 4.2). Furthermore, two measurements of sediment yield are presented, metric tons (t) and metric tons per hectare (t/ha). The latter is also known as specific sediment yield and will be referred to as such for the remainder of this paper.

During the period of observation, the average specific sediment yield for each sub-watershed in the study area was determined (Figure 4.3). The sub-watersheds are categorized from low specific sediment yield (0.001 t/ha) to high specific sediment yield (0.325 t/ha). Similar amounts of higher categorized sub-watersheds producing sediment yield can be found between the two watersheds. Differences can be seen in the northern portion of the Sink Creek watershed where specific sediment yield is categorized as low in a fairly large area. Purgatory Creek does not have an area of low specific sediment yield, but instead a few pockets throughout the watershed. Higher specific sediment yield occurs at more locations in the Purgatory Creek watershed compared to the Sink Creek watershed. Though, Sink Creek has more areas of the highest category between the two watersheds. Upstream from the flood control dams the sub-watersheds have an average specific sediment yield for the study area of 0.046-0.069 t/ha. The one exception is Dam No. 2, which is located on a tributary to Sink Creek. This location has a sub-watershed above the dam that is below average for the watershed (0.020-0.045 t/ha). Conversely, the downstream sub-watersheds of Dam No. 1, 2, and 4 are all in the second lowest category of specific sediment yield (0.020-0.045 t/ha)

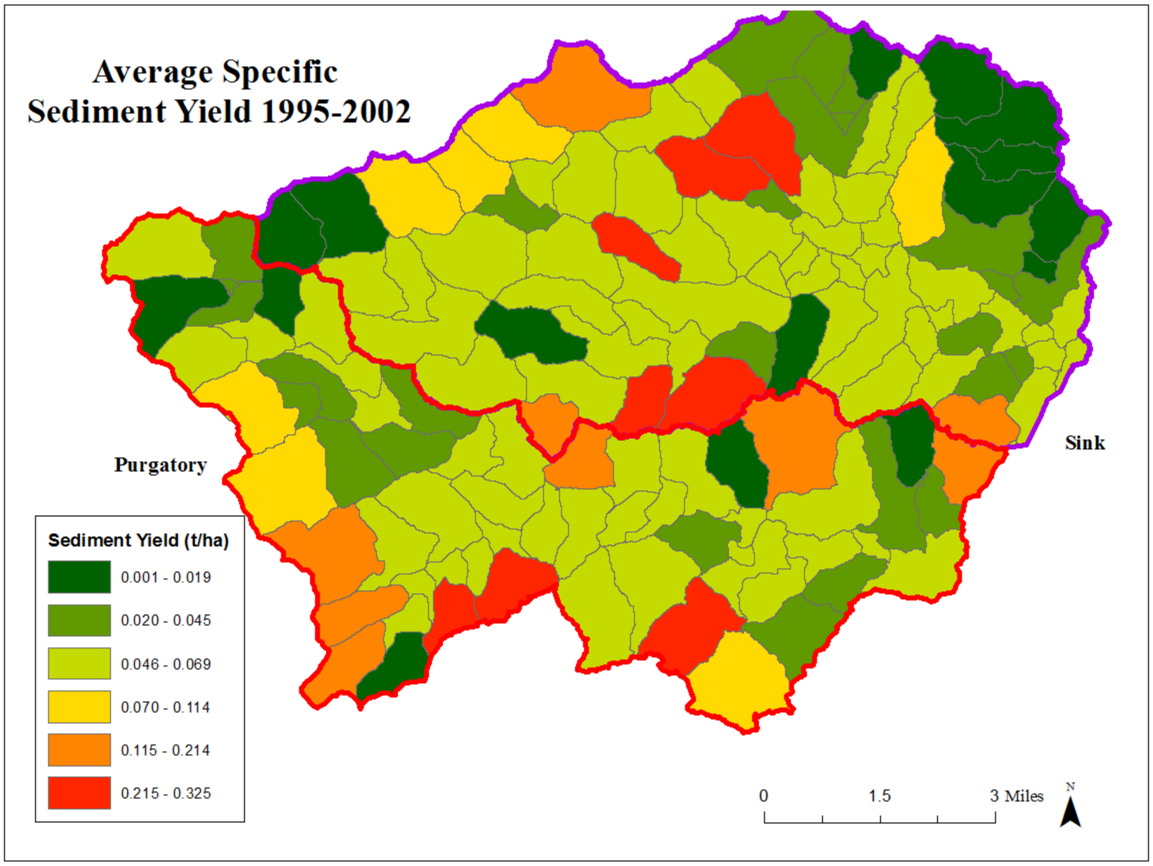



**Figure 4.3.** Yearly Average Specific Sediment Yield (t/ha) for Each Sub-Watershed in the Study Area.

Sink Creek was found to have the highest yearly total sediment yield and mean sediment yield (Table 4.2). Although the results are similar during most years, 1998 indicated the largest difference between the two watersheds. A difference of 1494t can was found, along with results showing that aside from 1998, the watersheds were fairly similar in yearly sediment yield produced (Figure 4.4). The total sediment yield for period of observation was 20836t for Sink Creek and 17160t for Purgatory Creek watershed.

**Table 4.2. Yearly Sediment Yield (t).**

| Sink Creek | | | Purgatory Creek | | |
|---|---|---|---|---|---|
| **Year** | **Total (t)** | **Mean (t)** | **Year** | **Total (t)** | **Mean (t)** |
| 1995 | 547.78 | 45.65 | 1995 | 481.18 | 40.10 |
| 1996 | 308.71 | 20.21 | 1996 | 236.01 | 15.73 |
| 1997 | 2192.51 | 175.30 | 1997 | 1946.25 | 154.55 |
| 1998 | 5838.67 | 486.56 | 1998 | 4344.08 | 362.01 |
| 1999 | 992.34 | 82.70 | 1999 | 843.00 | 70.25 |
| 2000 | 943.07 | 78.59 | 2000 | 804.58 | 67.05 |
| 2001 | 1421.59 | 118.47 | 2001 | 1180.03 | 98.34 |
| 2002 | 8591.80 | 715.98 | 2002 | 7324.78 | 610.40 |

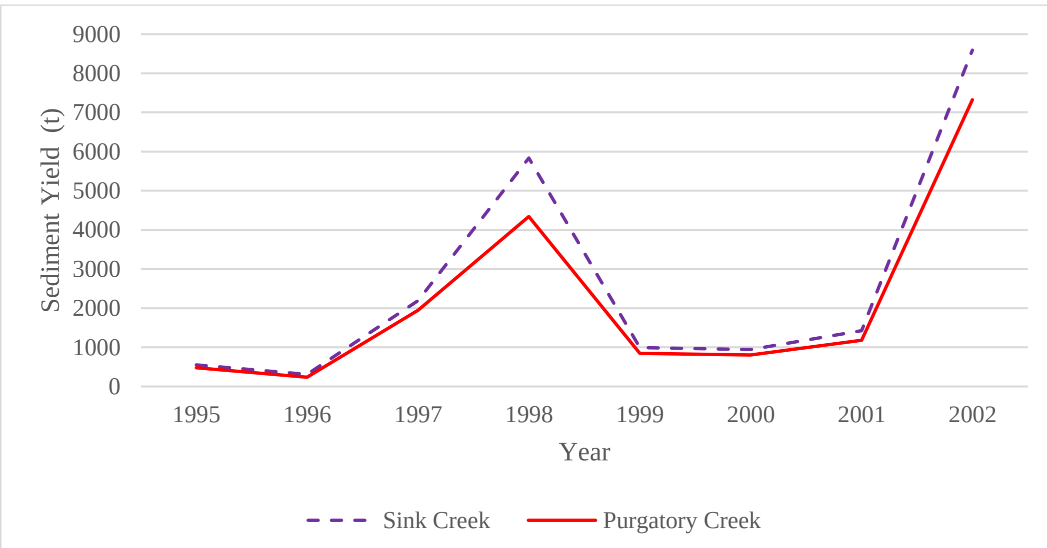



**Figure 4.4.** Sediment Yield (t) 1995-2002, Yearly Totals.

The results show that aside from 1998, Purgatory Creek watershed had a higher yearly specific sediment yield (Figure 4.5). For the period of observation, Purgatory Creek's total specific sediment yield was 1.95 t/ha, while Sink Creek's was 1.87 t/ha. Rather than comparing the amount of sediment alone, this measurement may give a better indication on which watershed is more effective at producing sediment. For both watersheds, 2002 had the highest specific sediment yield, while 1996 had the lowest.

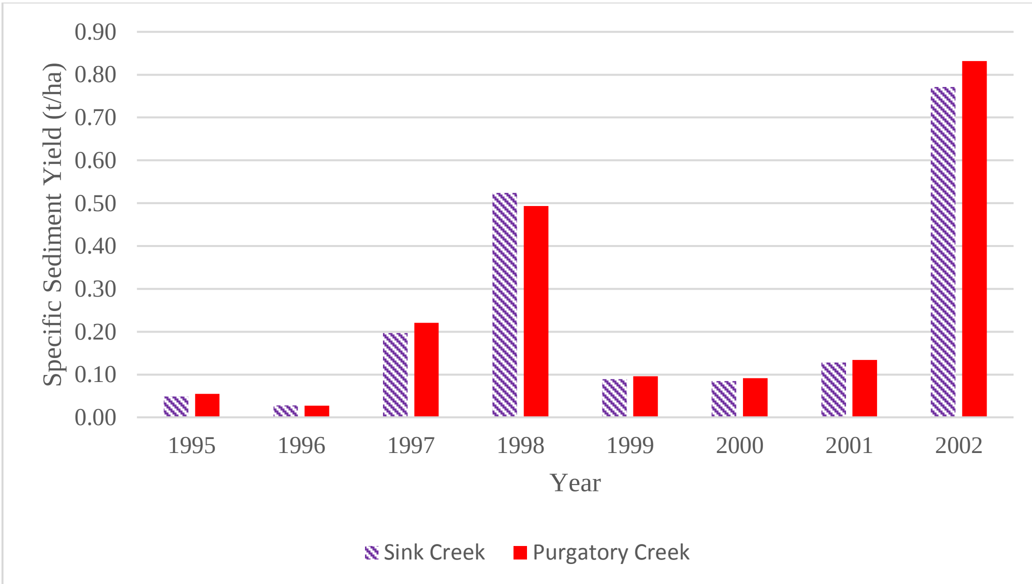



**Figure 4.5.** Specific Sediment Yield (t/ha) 1995-2002, Yearly Totals.

Similar to the yearly results, Sink Creek was found to have both higher total and mean sediment yield (Table 4.3). Also like the yearly results, a similar relationship in sediment yield for every month, except for month of October was found (Figure 4.6). The difference between the two watersheds during the month of October was 1455t.

**Table 4.3. Monthly Sediment Yield (t).**

| Sink Creek | | | Purgatory Creek | | |
|---|---|---|---|---|---|
| **Month** | **Total (t)** | **Mean (t)** | **Month** | **Total (t)** | **Mean (t)** |
| Jan | 748.72 | 93.59 | Jan | 590.18 | 73.77 |
| Feb | 495.30 | 61.91 | Feb | 380.17 | 47.52 |
| Mar | 800.76 | 100.10 | Mar | 671.84 | 83.98 |
| Apr | 597.78 | 74.72 | Apr | 526.19 | 65.77 |
| May | 628.29 | 78.54 | May | 545.32 | 68.16 |
| Jun | 1218.38 | 152.30 | Jun | 1125.71 | 140.71 |
| Jul | 3257.58 | 407.20 | Jul | 3017.83 | 377.23 |
| Aug | 1547.18 | 193.40 | Aug | 1300.00 | 162.50 |
| Sep | 2235.01 | 279.38 | Sep | 1573.29 | 196.66 |
| Oct | 6569.25 | 821.16 | Oct | 5114.87 | 639.36 |
| Nov | 1822.58 | 227.82 | Nov | 1558.69 | 194.84 |
| Dec | 915.65 | 114.46 | Dec | 755.82 | 94.48 |

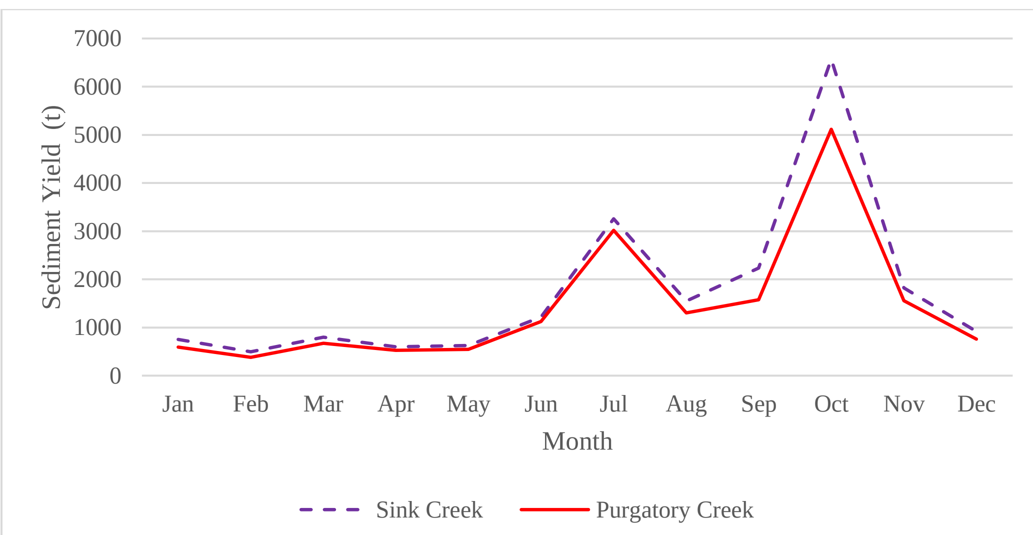



**Figure 4.6.** Sediment Yield (t) 1995-2002, Monthly Totals.

When comparing monthly specific sediment yield for both watersheds, Purgatory Creek is higher in nearly every month, except for February, September, and October

(Figure 4.7). For both watersheds, the most productive months in terms of specific sediment yield were July and October. While the least productive months were February and April.

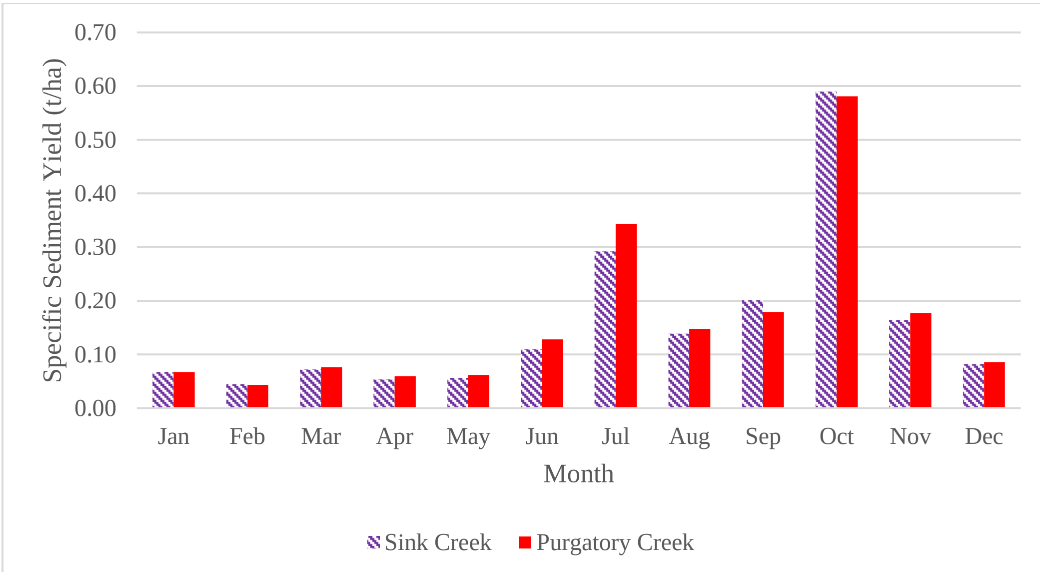



**Figure 4.7.** Specific Sediment Yield (t/ha) 1995-2002, Monthly Totals.

Both yearly and monthly precipitation totals were calculated and compared with sediment yield for both watersheds (Figure 4.8). The year of 2002 saw the highest precipitation total of 1577mm resulting in 8592t and 7325t of sediment yield for the Sink Creek and Purgatory Creek watersheds, respectively. The lowest precipitation total resulted in a total sediment yield of 308t for Sink Creek and 236t for Purgatory Creek watershed.

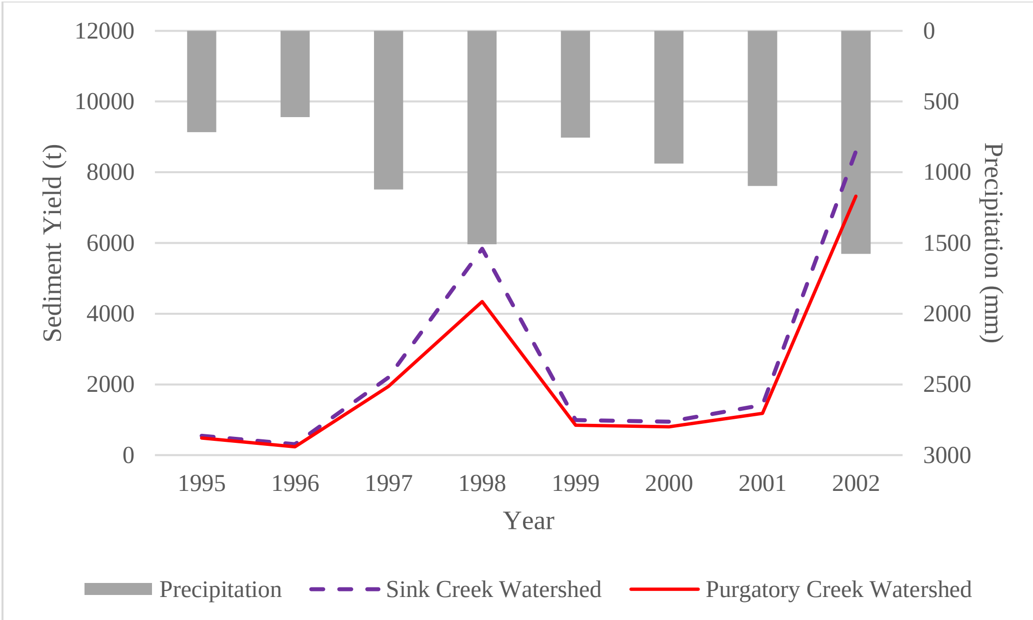



**Figure 4.8.** Yearly Total Precipitation (mm) and Sediment Yield (t) 1995 to 2002.

When comparing yearly sediment yield and precipitation, a strong correlation for both watersheds was found. This relationship was best explained exponentially, resulting with an $R^2$ of 0.96 for Sink Creek and an $R^2$ of 0.94 for Purgatory Creek (Figure 4.9).

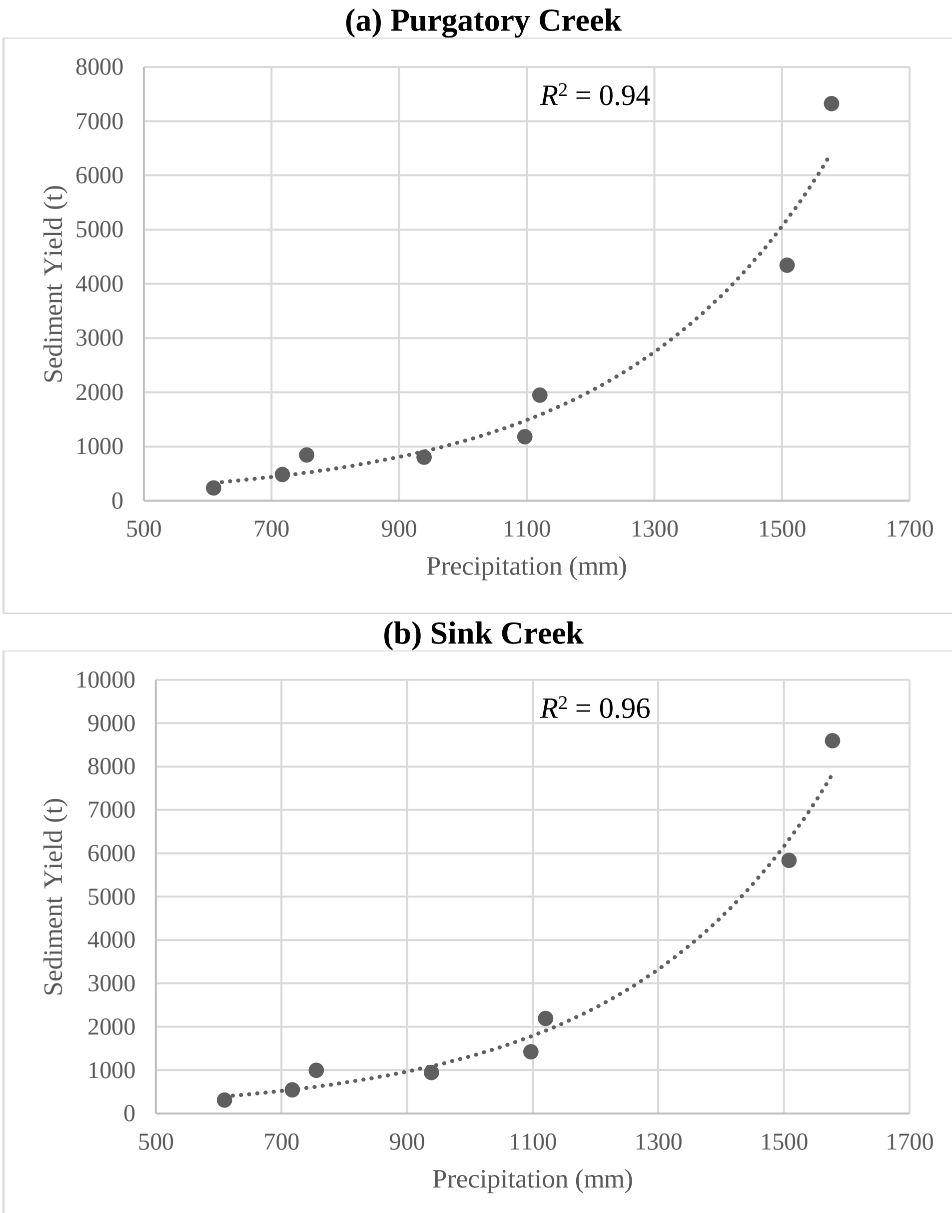



**Figure 4.9.** Yearly Precipitation (mm) vs Sediment Yield (t) 1995 to 2002.

A comparison of monthly precipitation and sediment yield indicated a nearly identical relationship between the two watersheds (Figure 4.10). One of the exceptions occurs during the months of September and October in 1998, during this time span Sink Creek produced approximately 600t more sediment than Purgatory Creek watershed.

Another exception is September 2002 where Sink Creek watershed produced approximately 700t more sediment than Purgatory Creek. Both of these differences took place during months where the total precipitation was near or greater than 400mm. For the majority of the period of observation monthly sediment yield was under 500t. For most cases, in order for sediment to exceed 500t, precipitation would need to be over 200mm. Months where sediment yield exceeded 500t with less than 200mm of rain, were most likely caused by one or two high-magnitude precipitation events. Whereas most months with high sediment yield most likely experienced multiple days of precipitation along with some high-magnitude events.

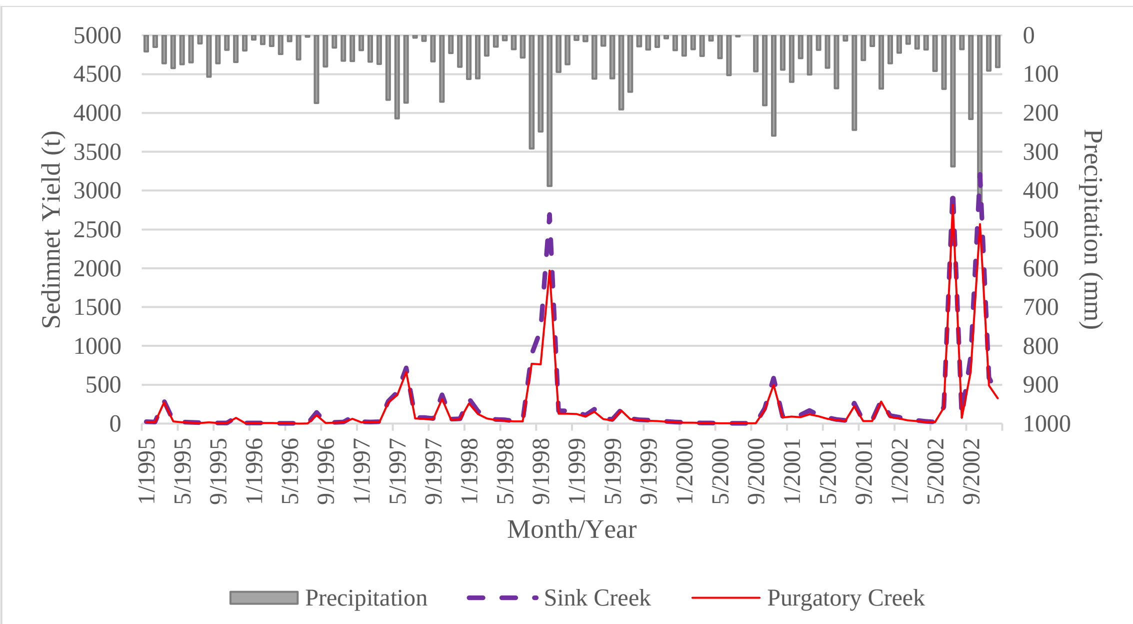
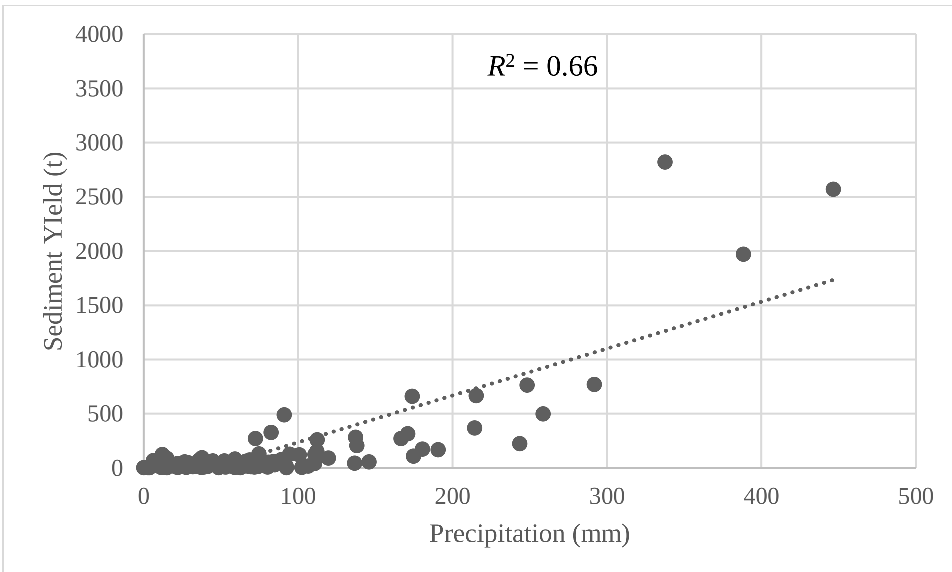



**Figure 4.10.** Monthly Total Precipitation (mm) and Sediment Yield (t) 1995 to 2002.

The relationship of monthly precipitation vs sediment yield for each watershed was determined (Figure 4.11). Unlike the yearly relationship, a linear equation was best suited for the monthly data. Purgatory Creek watershed has a slightly higher $R^2$ of 0.66 to

Sink Creek's 0.64. These values are significantly less compared to the yearly results. This indicates that monthly precipitation may not be as adequate at predicting sediment yield as yearly precipitation.

**(a) Purgatory Creek**




**(b) Sink Creek**

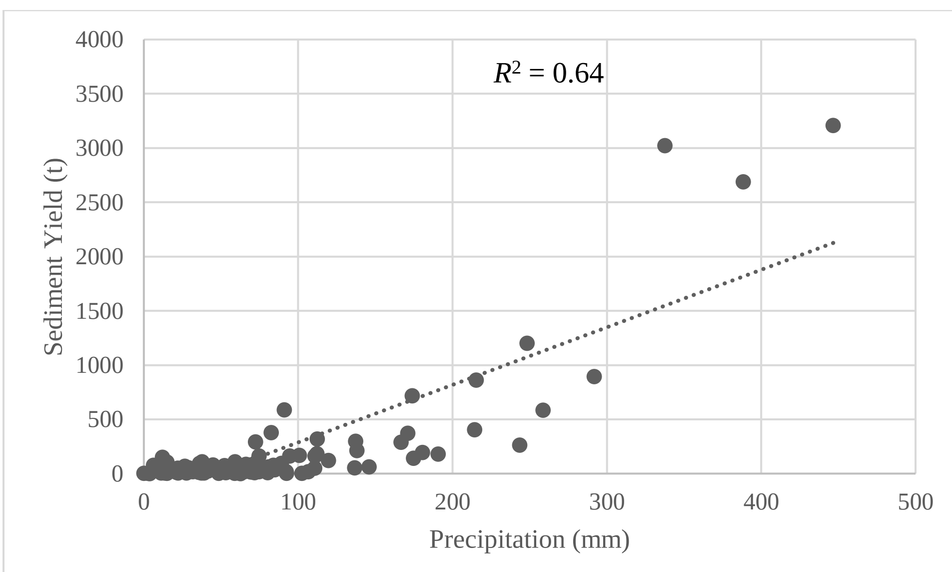



**Figure 4.11.** Monthly Precipitation (mm) vs Sediment Yield (t) 1995 to 2002.

### 4.3. Basin characteristics

Land use and land cover total areas and percentages were derived from the 2011 NLCD. The area of each land cover type, along with the percentage of the entire watershed was determined (Tables 4.4 and 4.5). The NLCD land use type, Evergreen Forest, dominates both watersheds encompassing approximately 17.27 $mi^2$ (39.85%) and 12.60 $mi^2$ (36.60%) for Sink Creek and Purgatory Creek watersheds, respectively. A group of land use types that may lead to higher runoff producing more erosion, thus higher sediment yield, are classified as the developed land use types. The NLCD divides these land use types into four categories (Tables 4.4 and 4.5). When the totaled, developed land use makes up 1.77 $mi^2$ (5.15%) of Purgatory Creek watershed and 1.63 $mi^2$ (3.77%) of Sink Creek watershed.

**Table 4.4. Purgatory Creek Watershed Land Use Types.**

| Land Use | Area ($mi^2$) | Percentage of Watershed |
|---|---|---|
| Barren Land | 0.01 | 0.02 |
| Deciduous Forest | 4.97 | 14.44 |
| Developed, High Intensity | 0.02 | 0.05 |
| Developed, Low Intensity | 0.32 | 0.94 |
| Developed, Medium Intensity | 0.10 | 0.29 |
| Developed, Open Space | 1.33 | 3.87 |
| Evergreen Forest | 12.60 | 36.60 |
| Herbaceous | 6.71 | 19.49 |
| Open Water | 0.00 | 0.01 |
| Shrub/Scrub | 8.36 | 24.29 |

**Table 4.5. Sink Creek Watershed Land Use Types.**

| Land Use | Area ($mi^2$) | Percentage of Watershed |
|---|---|---|
| Barren Land | 0.01 | 0.03 |
| Deciduous Forest | 6.25 | 14.43 |
| Developed, High Intensity | 0.02 | 0.06 |
| Developed, Low Intensity | 0.22 | 0.50 |
| Developed, Medium Intensity | 0.11 | 0.26 |
| Developed, Open Space | 1.28 | 2.95 |
| Evergreen Forest | 17.27 | 39.85 |
| Herbaceous | 7.08 | 16.34 |
| Mixed Forest | 0.00 | 0.01 |
| Open Water | 0.02 | 0.06 |
| Shrub/Scrub | 11.06 | 25.53 |
| Woody Wetlands | 0.00 | 0.01 |

For both watersheds, the majority of the developed area is in the eastern portion, near the city of San Marcos, TX (Figure 4.12). It can be seen that Purgatory Creek watershed has more developed area when compared to Sink Creek watershed (Figure 4.12).

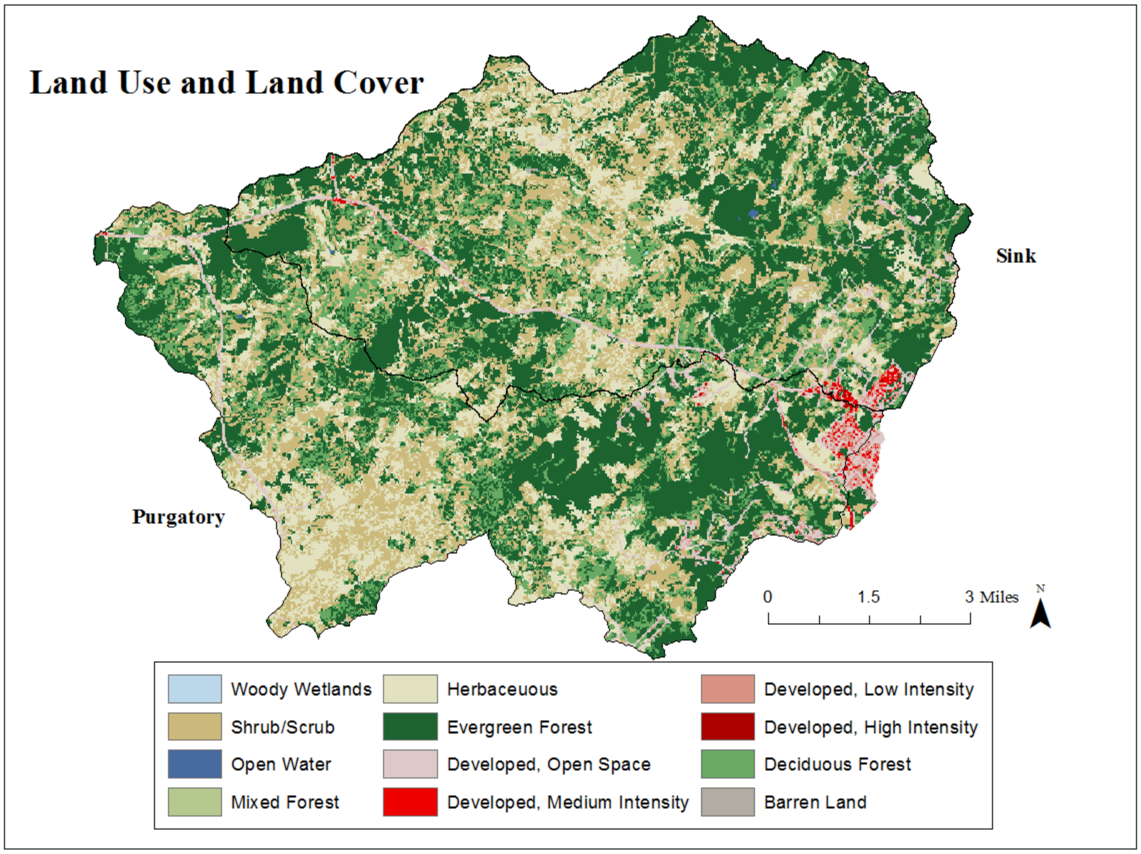



**Figure 4.12.** Land Use and Land Cover for the Study Area.

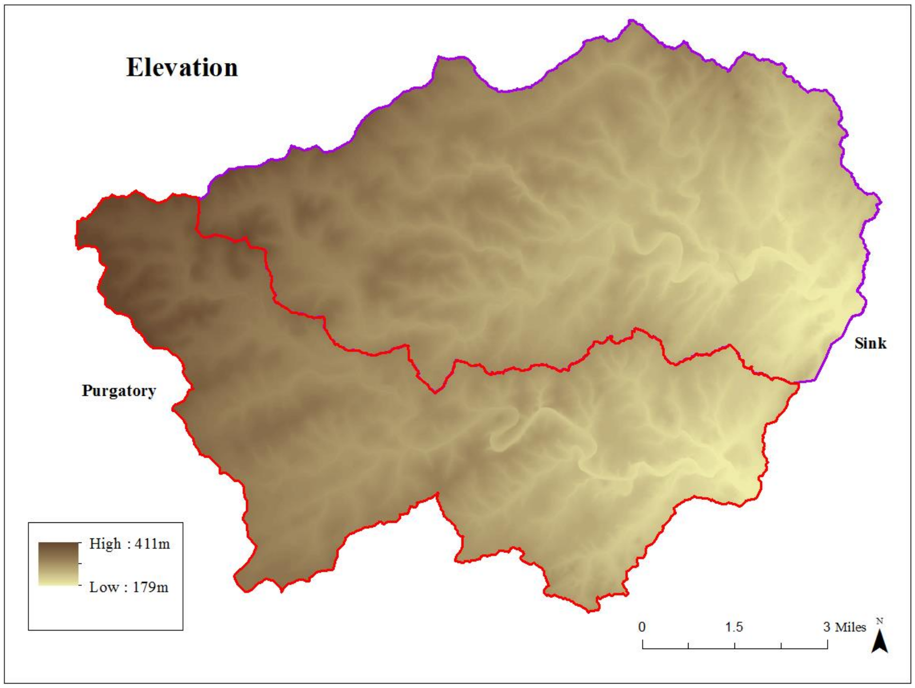
Topographic statistics showing the high, low, mean, and standard deviation for each watershed were derived (Table 4.6). Purgatory Creek has both the highest and lowest elevation points between the two watersheds. The mean elevation for Purgatory Creek is also 15m higher than Sink Creek.

**Table 4.6. Topographic Statistics for Sink Creek and Purgatory Creek Watersheds.**

| Watershed | High (m) | Low (m) | Mean (m) | SD (m) |
|---|---|---|---|---|
| Sink Creek | 392.47 | 181.58 | 275.94 | 39.09 |
| Purgatory Creek | 411.24 | 178.91 | 290.23 | 46.22 |

Both of the watersheds contain similar areas of high relief as indicated by the elevation and slope data, however Purgatory has slightly higher relief areas (Figure 4.13). These areas are primarily near the main channel of the stream, specifically, near and downstream from dam No. 5. Additionally, Purgatory Creek watershed consist of areas of relatively low relief in the western portion of the watershed. Within the Sink Creek watershed, many of the slopes are between 4.70 and 8.96 degrees (Figure 4.13). These areas are primarily at or near tributaries to Sink Creek in the central portion of the watershed.

**(a) Elevation**




**(b) Slope**

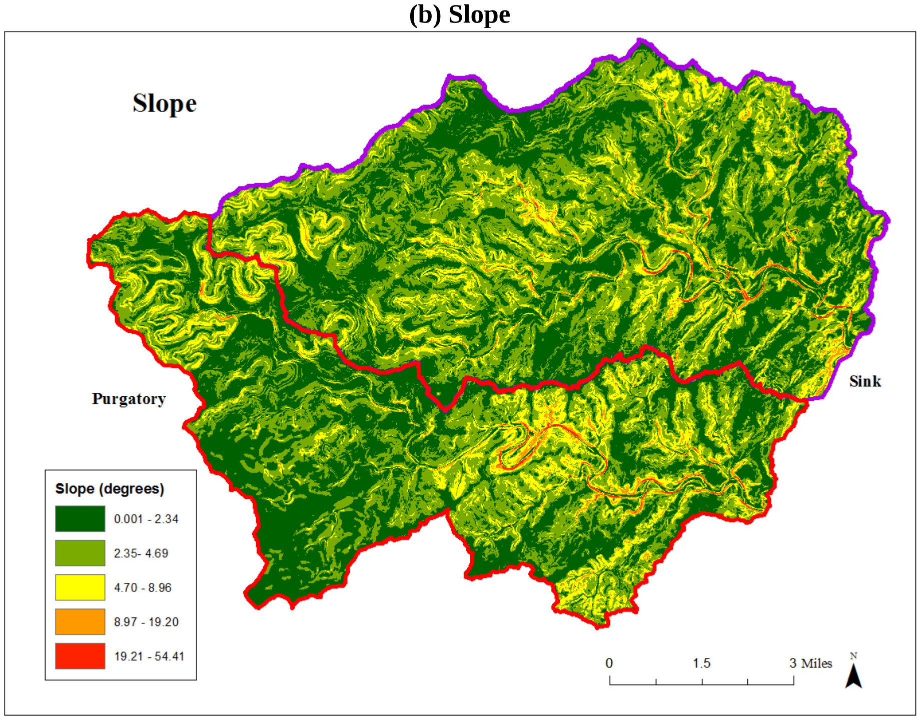



**Figure 4.13.** Elevation and Slope for the Study Area.

The drainage density used the NHD layer to determine the stream length totals for each watershed (Table 4.7). Drainage density is unitless with high drainage density defined as > 2.74, while low drainage density is < 0.73 (Horton 1945 p283). Purgatory Creek watershed has a slightly higher drainage density of 2.33, compared to Sink Creek's 2.27 (Table 4.7). The basin relief ratio for the watersheds were similar, with Sink Creek having 0.013 and Purgatory Creek of 0.012 (Table 4.7).

**Table 4.7. Drainage Density & Relief Ratio for Sink Creek and Purgatory Creek Watersheds.**

| Watershed | Drainage Density | Relief Ratio |
|---|---:|---:|
| Sink Creek | 2.27 | 0.013 |
| Purgatory Creek | 2.33 | 0.012 |

# 5. DISCUSSION

## 5.1. Comparison of results with other model applications

I calibrated a SWAT model to flow because of a lack of measured sediment data in the region. I used the SUFI-2 calibration method and obtained a best fit *E* value of 0.55 at the monthly timestep. The best *E* value out of all of the 200 simulations was 0.77. SWAT applications that didn't use the SUFI-2 method can be compared with the best simulation from my results. In the region, a monthly *E* value of 0.85 was obtained by Bumgarner and Thompson (Bumgarner and Thompson 2012) and a smaller application (140mi$^2$) resulted in *E* of 0.50 (Afinowicz et al. 2005). There are many studies that have used SWAT in state of Texas. The majority of the monthly *E* values for flow are acceptable (> 0.5) and seem to typically fall between 0.72 (Santhi et al. 2006) and 0.89 (Santhi et al. 2001). Unlike my study, these SWAT applications did not provide a range of possible solutions to account for uncertainty. Instead, values were obtained by calibrating the model until the best *E* was obtained.

Results fared well when compared to applications that did use the SUFI-2 model for calibration. One such application resulted in and *E* of 0.51 for calibration and 0.48 for validation. The *P-factors* were 0.73 and 0.65, respectively. While the *R-factors* were 0.58 for calibration and 0.54 for validation (Setegn et al. 2008). These results were opposite from mine in terms of the *P-factor* in that the calibration was smaller than the validation. Another SWAT application that used the SUFI-2 calibration methods lined up more similar with mine where three out of four model applications had higher *P-factor's* in the validation (Jajarmizadeh et al. 2012). Overall my highest *E* of 0.77 at the monthly timestep was comparable with others. On the other hand, my validation of 0.43 was lower than most validations occurring in the region and Texas.

Although I cannot compare my results with the study that called for a more focused model in the study area (Sansom and Xia 2010) due to different scales, some of their reported findings were similar to mine. Most notably, like their study, my study found that the urban areas were not the most prominent source of sediment in the study area. This is, among other factors, mostly like due to urban areas existing in parts of the study area where thin soils dominate the landscape (Sansom and Xia 2010).

More recent modeling efforts using the same model as Sansom and Xia (2010) (Hydrologic Simulation Program- Fortran (HSPF)) identified similar areas of higher erosion compared to my modeled results (SMWI 2017). Conversely, the same study did not find areas in the upstream portion of the watersheds producing the same amount of sediment as my results found. One possible reason for this is the number of sub-watersheds used in their study differed compared to mine. Also, they did not include the tributaries in the upper portions of the watersheds in their modeling. This could be due to the intermittent nature of the streams in these areas. My model used the NHD dataset to account for all of tributaries. Another reason they may have not used all of the tributaries is the presence of the flood control dams. These dams most likely trap sediment, allowing it settle and be deposited in their reservoirs. This makes it difficult to confidently model the amount of sediment leaving each watershed as a whole. Although it shouldn’t lower confidence in results of sediment yield for single sub-watersheds upstream from the dams.

## 5.2. Lack of measured sediment data for the region

The goal of this project was to compare sediment yield in two similar sized watersheds to better understand their relationship with basin characteristics and precipitation. I calibrated a SWAT model to discharge at a USGS stream gauge downstream from the two watersheds. By doing this calibration, the model's results most likely better represent the hydrologic process occurring within the watershed. Due to a lack of sediment monitoring at or near the study area, I was unable to calibrate the model to sediment yield. The closest collected sediment data was at USGS stream gauge 0817100 on the Blanco River in Wimberly, TX. Less than 30 samples were collected between the years and 1996 and 1998. The samples were collected as grab samples, most during times of high flow. Although acceptable methods exist that can estimate sediment based on flow (Runkel et al. 2004), less than 30 samples may lead to results accompanied with a high degree of uncertainty. This uncertainty not only manifest itself in the limited number of samples, but also how and where the samples were collected.

Therefore, to truly calibrate a hydrologic model, such as SWAT, to sediment yield for these watersheds, continuous data collection of sediment would need to occur at multiple locations. Due a lack of immediate issues associated with sediment effecting infrastructure, as well as the cost of operating and maintaining such equipment, continuous sediment data collection most likely not occur anytime soon within the study area.

## 5.3. SWAT model limitations

Results from complex hydrologic models, such as SWAT, should be interpreted with a degree of uncertainty. Model performance measures are used to lessen the uncertainty of the results, though even with satisfactory performance measure, certain parameters of the model could be inaccurate in representing the hydrologic system. Uncertainty in capturing weather conditions, such as isolated storms, may lead to inaccuracies in model outputs. Not capturing accurate weather events in the watershed may make it difficult to calibrate and validate the model. For this study, only five weather stations were used. This limited number of weather stations may explain some of the over and under estimation of flow. SWAT assigns each sub-watershed a weather value based on the nearest station to the polygon's centroid. With only five stations, some of the sub-watersheds may have been assigned an inaccurate weather value. Additionally, due to the high-magnitude precipitation events that occur over small areas within the region, weather stations may not be as precise in capturing representative amounts of precipitation. Again, this phenomenon may explain the significant difference in the un-calibrated modeled flow data vs the measured data.

When capturing the topology of the landscape, a certain level of uncertainty exists when using DEMs. For this study, 10m DEMs were used. The uncertainty of DEMs increases in areas of high relief. When modeling sediment transport, it is in these areas where DEMs may fail to capture all of the possible areas of where sediment could be deposited. Those that have addressed this issue, specifically when modeling sediment yield, have found that DEMs under 50m produced the best results (Chaplot 2005). This does not mean that areas of low relief should not be considered more accurate, as these areas may not capture the true elevation. In the end, DEMs are an estimation of the earth's surface and if they lead to adequate/acceptable results, then the uncertainty can be tolerated.

Both the National Land Cover Dataset (NLCD) and the Soil Survey Geographic Database (SSURGO) are used extensively in multiple disciplines of research. Although widely used, limitations of the datasets should be noted. For this study, the most recent available data was used in the SWAT model and to quantity the land cover types. The 2011 NLCD, at the time of this research six years old, may not represent land cover types occurring presently in each watershed. Furthermore, the NLCD is a 30m raster datatype. Fracturing the landscape into 30m x 30m grid may lead to a misrepresentation of a given land cover type. Unlike the NLCD, the SSURGO was represented by a vector datatype. Soil maps conducted at the County level help created the SSURGO. This study used the 2012 SSURGO. Even though the SSURGO is five years old, soil composition most likely does not change much in such a short period of time.

As mentioned in detail earlier in this discussion, the modeled sediment yield from this study carries a degree of uncertainty. This uncertainty is due to the inability to calibrate the model to sediment because of limited measured sediment data. Fortunately, the area does not contain a lack of measured water discharge data. Therefore, SWAT was calibrated to flow for an eight-year timespan at a USGS stream gauge downstream from both watersheds. Calibrating the model to flow may lead to results that better represent the hydrologic processes of the watershed.

Due to the popularity of the SWAT model, entire papers outline how to properly calibrate the model to various measured data (Arnold et al. 2012). Furthermore, programs such as SWAT-CUP, provide multiple approaches for calibration. For this study, I used the SUFI-2 approach from the SWAT-CUP program. This approach uses multiple simulations with a given range of parameters and an objective function to try and fit the model to. Obtaining a suitable model performance measure does not necessarily mean the model is calibrated. Rather, a set of parameters with a range of values may better represent a calibrated SWAT model. Providing a range of value parameters in lieu of a single set of parameters acknowledges uncertainty both in the model itself, as well as the measured values used to calibrate the model. USGS stream gauge flow measuring equipment, as with any precise measuring equipment, may malfunction or misread data. Therefore, to account for possible misrepresentation of measured data, programs like SUFI-2, were created (Abbaspour et al. 2004). When a range of values are provided as a solution for a calibrated model, there may be a less chance of misrepresentation of hydrologic factors. In other words, when a model is calibrated by changing parameter values until a model performance value its achieved, the result could include values that do not make hydrological sense. Consequently, presenting a range of values as an answer for a calibrated model seems appropriate in order to best represent the uncertainty of the results.

Even when using the SUFI-2 model, some subjectivity is injected into the results. The user chooses the parameters to calibrate, the range of the parameters, and the method to change the parameters value. A sensitivity analysis may be conducted before the calibration, although the process may be time consuming. This study primarily used parameters and their values from a nearby SWAT application. The sensitivity analysis from the SUFI-2 model indicated that the most sensitive parameters shared the same method of adjusting the values. These parameters used a percentage rather than a replacement for their value adjustments during the simulations. Because these parameters may have had a larger range of possible values compared to the other parameters, this could have resulted in greater impacts on the sensitively analysis. Any set of parameters and their values can be adjusted to obtain an adequate model performance. It is up to the modeler to decide if the adjusted parameters are reasonable for the study area.

### 5.4. Basin characteristics relationship with sediment yield

Areas of higher relief were expected to a have a higher sediment yield. These areas consist of steep slopes that are capable of transporting greater amounts of sediment from overland flow, or erosion. Results found that the areas of higher relief were not necessarily the areas with the greatest sediment yield. This relationship was most evident when observing specific sediment yield during the period of observation in the Purgatory Creek watershed. The southwestern portion of the watershed, where relative low relief is predominant, had some of the most productive sub-watersheds in terms of sediment yield for the entire study area (Figure 4.3). These results indicate that for this study, area of steep slopes was not a good indicator of sediment yield.

One explanation for the steep slopes not producing a large amount of sediment yield is the soil type. The limestone plateaus in the study area have primarily an outcrop complex soil types. These soils are thin and potentially highly erodible. They are potentially highly erodible because some of the slopes may not have any soil at all, only exposed limestone. In these areas, there will be very little soil to erode, thus limiting sediment yield. Another reason for steep slopes not being the most productive areas may be due to the quality of the data. I used a 10m DEM for this study, which was well below the recommended 50m to accurately measure sediment yield (Chaplot 2005). Even so, this resolution may have not have captured some of the areas with higher relief. These explanations may explain why some of the steepest slopes in the study area produced low to moderate sediment yield.

In both watersheds, the land use and land cover are similar. Differences were found in the Purgatory Creek watershed, where it contained a slightly higher urban classified land use compared to Sink Creek watershed. This was true in both in area and percentage of total (Tables 4.4 and 4.5). The urban areas in each watershed were expected to produce high sediment yields due to impervious cover increasing runoff.

Results indicate that the southwestern portion of Purgatory Creek watershed was the best producing in terms of specific sediment yield. Figure 4.3 shows (with the exception of one sub-watershed) this area's sub-watersheds are classified as either the first, or the second highest in producing sediment yield for the study area. As discussed previously, relief was not always found to be the best indicator for sediment yield. One indicator that may better explain the higher specific sediment yield in this area is the land cover type. This area consists of the largest concentration of the herbaceous land cover type in the entire study area. Shrub/scrub classified land cover is also prevalent in the area. These areas are comprised of grasslands, with little forest cover and Rumple-Comfort association (RCA) soil type. Although the RCA soil type is the most dominant in the study area, not all areas with this soil type produced a high amount of sediment yield. I can conclude that the combination of herbaceous and shrub/scrub, along with the soil, type, was the best indicator of sediment yield.

High-magnitude precipitation events can produce overland flow that has the potential to entrain and transport soil to stream channels. Therefore, a strong correlation was expected between precipitation and sediment yield. Both watersheds indicated a similar relationship with monthly precipitation averages and sediment yield. With Sink Creek having a $R^2$ of 0.64 and Purgatory Creek a $R^2$ of 0.66, precipitation alone showed to be a marginal indicator of sediment yield.

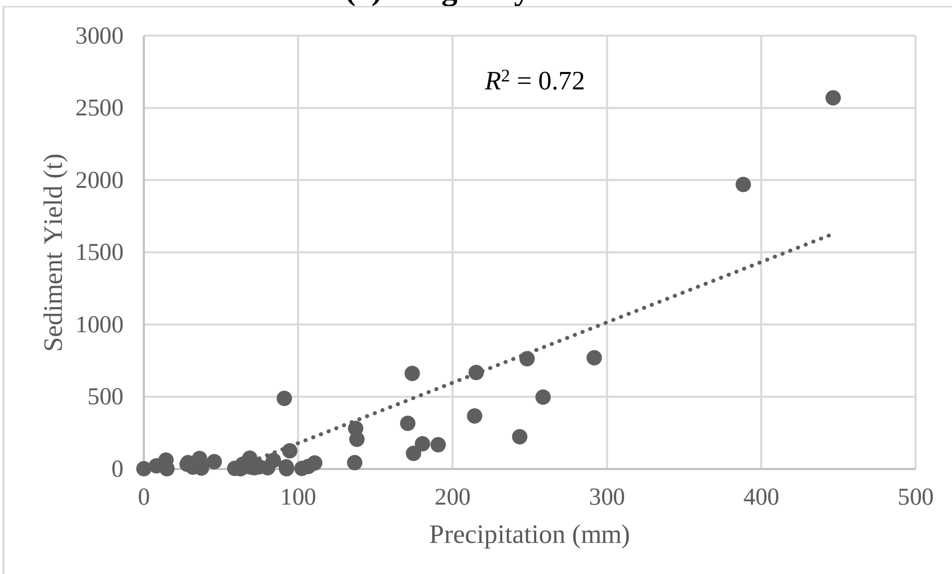
To further evaluate this relationship, wet and dry months were separated based on average precipitation. The wet months included May, June, and August to November. While the average dry months were January to April, July, and December (Table 5.1).

**Table 5.1. Monthly Average Precipitation, Highest to Lowest.**

| Month | Precipitation (mm) |
|---|---:|
| Oct | 164.28 |
| Jun | 113.69 |
| Aug | 111.98 |
| Sep | 109.56 |
| Nov | 96.14 |
| May | 82.81 |
| Jul | 73.55 |
| Dec | 67.90 |
| Mar | 65.81 |
| Apr | 55.48 |
| Jan | 53.96 |
| Feb | 45.39 |

After separating the dataset, both watersheds indicated that precipitation was a better indicator during the wet months. Specifically, both watersheds showed an increase in the $R^2$ of about 0.10 (Figure 5.1). A linear relationship still exists for both watersheds. Others have also found the wet months to be a better predictor of sediment yield (Fournier 1960).

**(a) Purgatory Creek**




**(b) Sink Creek**

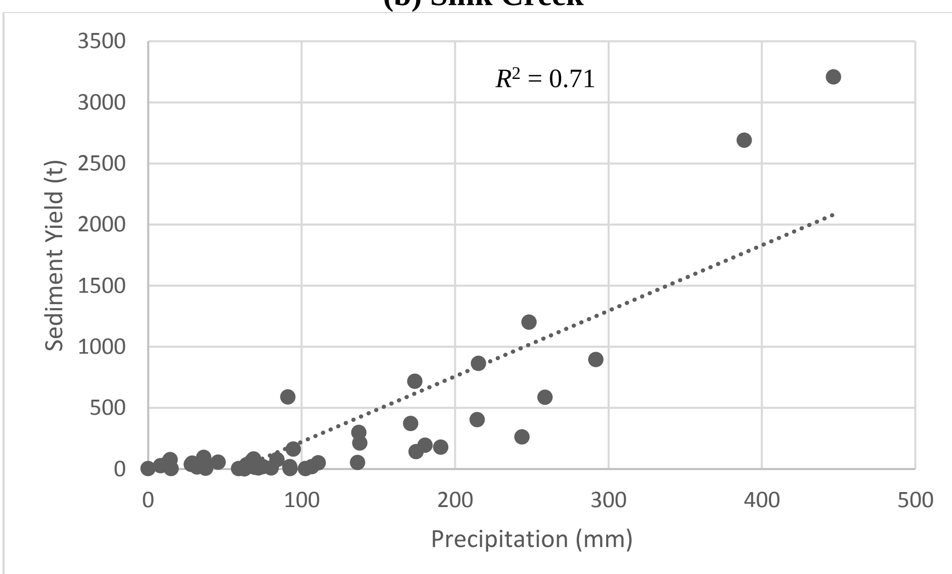



**Figure 5.1.** Monthly Precipitation (mm) vs Sediment Yield (t), 1995-2002, Wet Months.

After separating the dry months from the dataset, it was observed that a possible outlier was present (Figure 5.2). For the dry months, nearly all of the monthly precipitation totals were under 150mm, with two being over. One of these two was the month of July in 2002. This month experienced 337mm of precipitation in total. This was the third wettest month of the entire dataset and 263mm over its average of 74mm. Due to these factors, this value was removed from the dry months results.

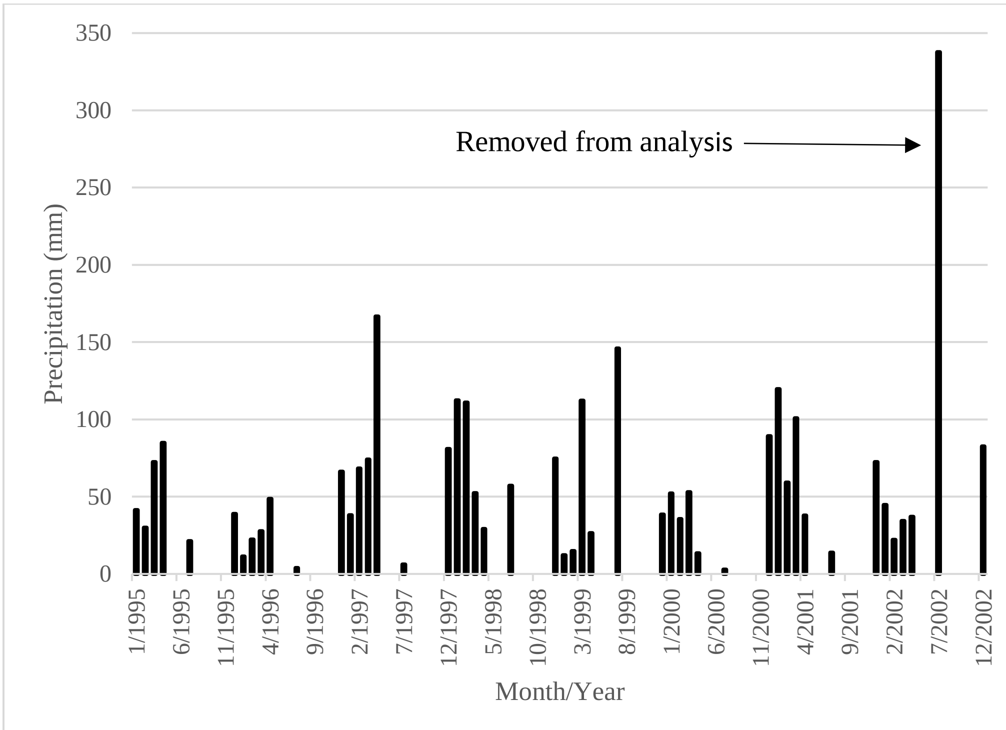
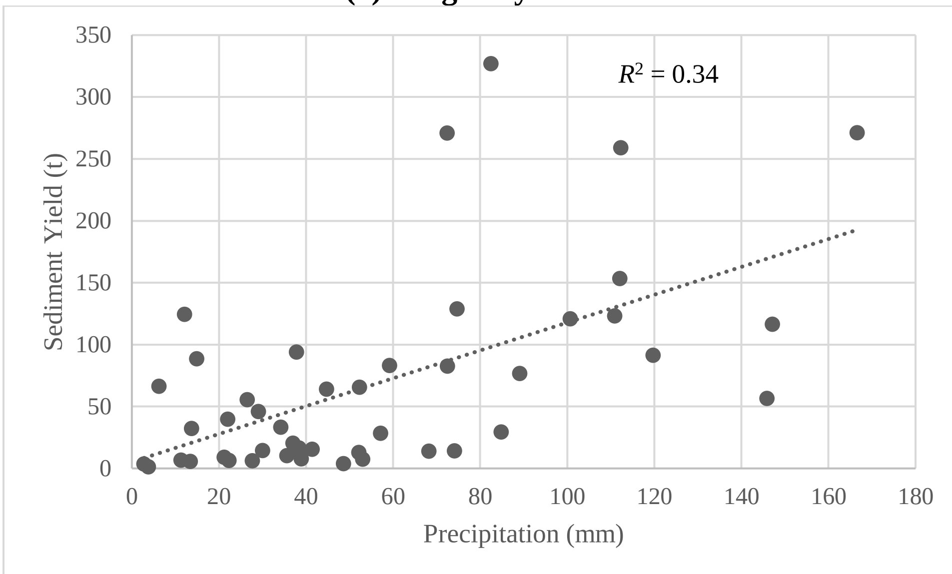



**Figure 5.2.** Outlier from the Dry Months Dataset.

Once the outlier was removed, a better representation of the relationship of precipitation and sediment yield was observed. Statistically, there was little correlation between precipitation and sediment yield. The results indicated a weak linear relationship. Sink Creek had an $R^2$ of 0.35, while Purgatory Creek had and $R^2$ of 0.34 (Figure 5.3). This relationship could be explained by high precipitation events occurring less frequently during these months. Instead, these months most likely experience frequent small-magnitude precipitation events. Such precipitation events may not produce overland flow, thus limiting entrainment and sediment reaching the stream.

**(a) Purgatory Creek**




**(b) Sink Creek**

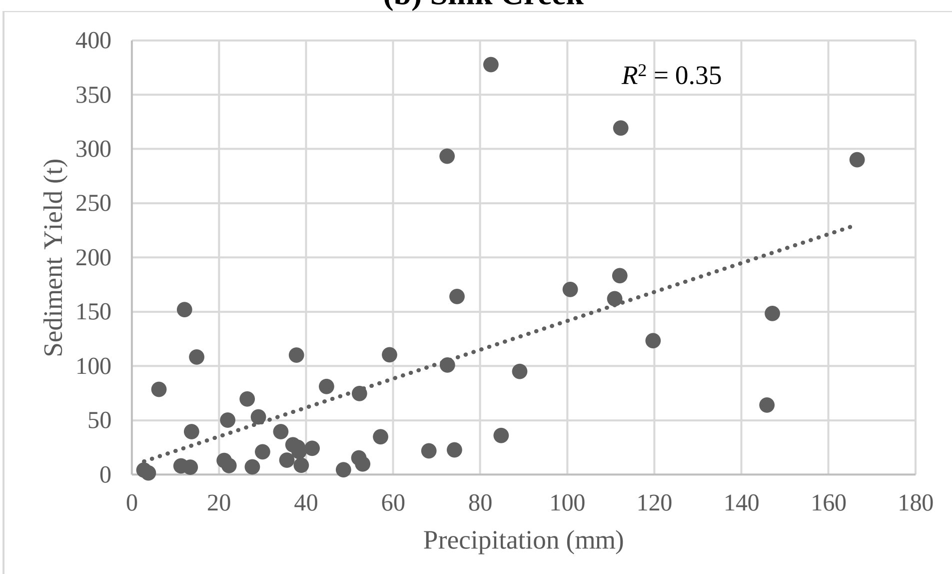



**Figure 5.3.** Monthly Precipitation (mm) vs Sediment Yield (t), 1995-2002, Dry Months.

Due to the study area's low-frequency of effective precipitation events, as well as the semi-arid climate, it was hypothesized that greater than 50% of the sediment yield would occur from less than or equal to 25% of the precipitation events (Langbein and Schumm 1958). The data for this study is separated by the monthly timestep due to the increased uncertainty of modeled daily results. Therefore, precipitation events cannot be examined by themselves. However, changing the hypothesized timestep from precipitation events to monthly total precipitation may result in a better understanding of the relationship between precipitation and sediment yield.

The top 25% total precipitation months were identified (Figure 5.4). The seven months ranged from 244mm to 447mm. Next, the sediment yield from those months were totaled and compared against the total for the rest of the months. This process was done for both watersheds (Figure 5.5). The results reveled that both watersheds had greater than 50% of their total sediment yield occurring from the top 25% of the total monthly precipitation. Specifically, Purgatory Creek watershed had 56% (9613t) of its total sediment yield occurring these months, while Sink Creek watershed had 57% (11870t). When comparing the two watersheds, the relationship is similar. What these results may indicate is an overall strong relationship between sediment yield and larger amounts of precipitation. This is likely due to the clayey soils that are prevalent in the study area. In order to erode clayey soil, a significant amount of overland flow must occur. The months that have the highest amount of total precipitation most likely had high-magnitude precipitation events which resulted in higher amounts of sediment entrainment. Overall these results are consistent with areas of similar climate and physiographic characteristics.

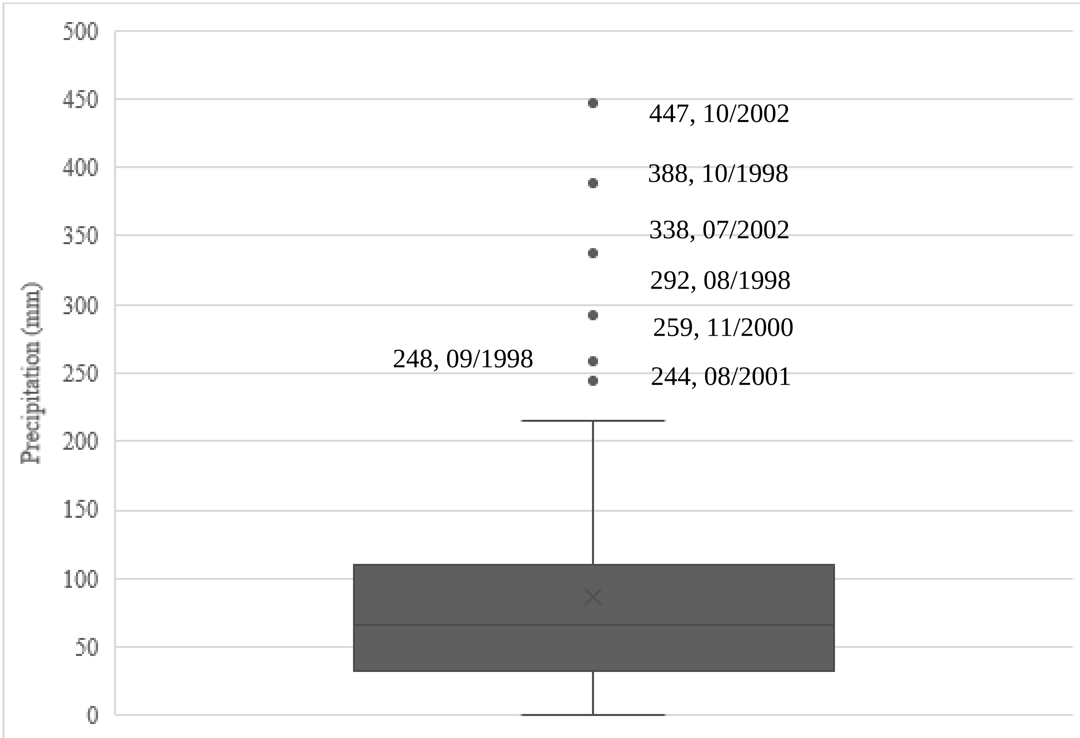
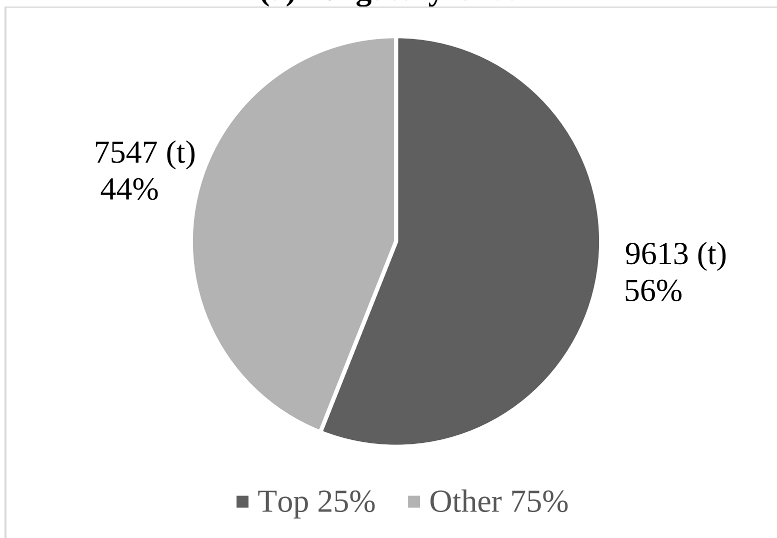


**Figure 5.4.** Top 25% of Total Monthly Precipitation (mm) 1995-2002.

**(a) Purgatory Creek**




**(b) Sink Creek**

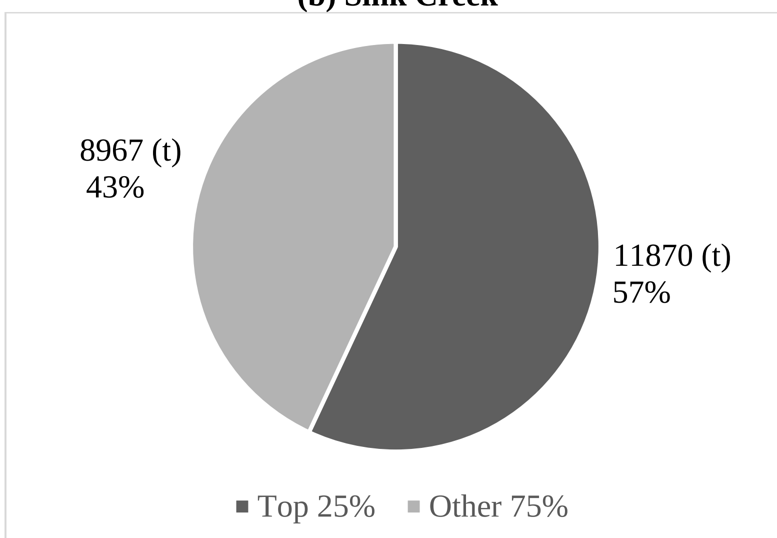



**Figure 5.5.** Comparison of Sediment Yield (t) for the Top 25% of Total Monthly Precipitation vs the Other 75%.

### 5.5. Best management practices

The results identified sub-watersheds that have the potential of producing a higher sediment yield and sediment runoff. Some of the highest yielding sub-watersheds were located in areas of primarily rangeland, upstream from the flood control dams. Other sub-watersheds with high sediment production were identified in the downstream portions of the study area, closer to the city of San Marcos. With forecasted population growth occurring primarily in the Purgatory Creek watershed (SMWI 2017), best management practices (BMP) can be implanted to lessen the amount of sediment reaching the creeks and possibly the San Marcos River. Not only is sediment a concern, but bacteria, phosphorus, and nitrogen that may accompany sediment runoff could have negative impacts should exceeding amounts be introduced to the water column.

For areas in the upstream portion of the study area, a simple riparian buffer-strip can be added to capture sediment and other possible pollutants from runoff. It has been found that the width of the buffer-strip plays the largest role in capturing runoff from nonpoint source (NPS) pollution (Lee et al. 2003, Lee et al. 2004). Guidelines on the exact width of the buffer-strip, as well as the type of vegetation to use, can be adopted from others that have used similar BMPs in the region. In intermittent steam channels, gully plugs (or check dams) may be beneficial in trapping sediment and other NPS pollutants. Most gully plugs are constructed with cobble stone, which can be placed in the channel using a front-end loader (Wang et al. 2009).

Designing a BMP strategy in an urban environment requires careful planning as the structures (in this case most likely roads and neighborhoods) are being built. New development in the region has included BMP in their design. The most prevalent of these are retention ponds, also referred to as storm waters water detention basins (SDB). The SDB act a filter and has been shown adequately capture sediment and other NPS (Hogan and Walbridge 2007). With the projection of urbanization occurring, especially in the Purgatory Creek watershed, such SBD-BMP should be included in the planning.

Modeling the effects of BMP in the study is continually being conducted (SMWI 2017). Although the model of choice for such efforts is the HSPF, SWAT also allows for such modeling. As pointed out earlier in my discussion, the number of sub-watersheds being used in other modeling efforts differs from mine. Most notably in the upper portions of the watersheds where fewer sub-watersheds are being used. It has been found, when using SWAT that the best results in modeling effects of BMP stems from sub-watershed size. An adequate sub-watershed size of approximately 4 percent of the entire watershed is recommended (Arabi et al. 2006). My research found that stricter standards of 3 percent have been recommend for modeling sediment yield (Jha et al. 2004; Migliaccio and Chaubey 2008). Therefore, the sub-watersheds delineated for this study may be useful in future applications of modeling BMP using SWAT. The results could then be compared to others that are using HSPF in their modeling efforts.

The results of this study alone do not specify where BMPs to control NPS pollution from runoff should be implemented. Rather, more detailed modeling and field work should be conducted before BMPs are placed. With that caveat in mind, the results of this study may be beneficial to planners by providing a high-level examination of where problem areas could reside in the study area. Therefore, my direct recommendations for planners and developers, in terms of BMP to control NPS runoff and sediment in the study area are as follows:

- Focus BMP construction in the upper portions of the watersheds.
    - The use of riparian buffer-strips and gully plugs are recommended for the upper reaches.
- Look to neighboring cities which have successful BMP implementations.

- These can be used as reference conditions for assessing management options for similar physical features such as, intermittent streams, soil type, and land-cover type.
- Before BMP construction, model the study area with the proposed changes to gain insight on potential system responses.
  - We recommend using multiple models and calibrations to NPS pollutants if possible.
- Set-up a plan for up-keep, maintenance of the structures, and adaptive management for new designs.
  - This is especially important following major flood events or land use changes.
  - This may involve plans to manage and or remove accumulated runoff sediments.

In summary, the above recommendations are an applied management-based contribution from this study's results. More detailed modeling, as well as field work, may lead to better recommendations and exact placement of BMPs in the study area.

## 5.6. Future studies

One of the advantages of using a widely applied model, like SWAT, is that others may easily replicate and build upon the methods. During this study, my goal was to compare results from a model that may not be the most precise. I tried to lower the uncertainty of the modeled results by calibrating flow to a stream gauge downstream from the study area. Future studies may further lessen the uncertainty of the model by measuring sediment runoff for both of these watersheds. In doing so, one could then conduct a calibration not only to flow, but to the measured sediment data.

Results showed that specific land cover types combined with specific soils were the best indicator for specific sediment yield. Grasslands with limited tree cover were found to the most productive in the Purgatory Creek watershed. Being that land cover was the best indicator for sediment yield, future studies could conduct a land cover change analysis for both watersheds. I used land cover types from 2011. Since 2011, the population has grown significantly in these watersheds. One could replicate the methods I outlined in this paper, only changing the land cover type to a more recent year. Then, a comparison of specific sediment yield can be conducted.

Another uncertainty that I did not address was how much sediment is being trapped by the dams in the watershed. My results found that the sub-watershed above each dam, with the exception of Dam No. 2, have an overall average specific sediment yield for the study area. Dam No. 2 in Sink Creek had a below average specific sediment yield. A future study could determine sediment accumulation rates by comparing highly precise LiDAR data. LiDAR was flown in 2008 over the study area. New LiDAR data, although proposed, was not yet ready for processing at the time of this study. A simple GIS comparison analysis of these data at the five flood control dams may lead to a better understanding of how much sediment these dams are trapping.

Due to increasing population in the study area, runoff carrying sediment and other NPS pollutants may increase. This may have negative effects to downstream ecosystems, specifically the San Marcos River. Modeling efforts with BMP using the HSPF model are being conducted. A future study may use my sub-watersheds to model BMP. Using two hydrologic models, SWAT and HSPF, may decrease the uncertainty of which BMP should be implemented.

Lastly, future studies can be conducted on the relationship with sediment yield and precipitation. My results were consistent with past studies which showed the majority of the sediment comes from 25% of the wettest months. With a better calibrated model, future studies may compare a single storm event with sediment yield. Such a study may increase our knowledge of how much erosion occurs from a single storm event in the study area.

# 6. CONCLUSION

A well-calibrated model, such as SWAT, can produce an accurate measurement of the sediment yield for a given watershed; however, a lack of measured sediment data for calibration combined with the complexity of these watersheds may have increased the uncertainty of these modeled results. My goal for this research was not to obtain a highly precise measure of sediment yield, but rather to generally compare two similarly sized watershed's sediment yield at a given point. The purpose of this comparison was to obtain a better understanding of which variables are more important to erosion.

Results from the modeling indicated that Sink Creek watershed produces more sediment (t), while Purgatory Creek watershed showed to have a higher specific sediment yield (t/ha). Although it was hypothesized that areas with greater amounts urbanization in the watersheds would lead to higher erosion rates, thus possibly more sediment yield, this was not found not to be the case. Instead, higher erosion areas were best predicted by the combination of land use and soil type. Furthermore, results found that areas of high relief were not a good indicator of erosion in this study area. This may be due to the lack of soil on the steep slopes or the lack of precision in the GIS data itself. Yearly precipitation was found to be a better indicator of predicting sediment yield than monthly precipitation. The results also showed that more than 55 percent of total sediment yield occurred during the top 25 percent of months with the highest precipitation.

The flow calibration results at the monthly timestep compared well with other SWAT applications in the region, as well as the state of Texas. My validation results were lower than most when compared to the region and the state of Texas. Recent modeling efforts using the HSPF model in the study area identified similar areas as my results producing higher amounts of sediment. The same modeling effort differed from in that fewer sub-watersheds were used, thus identifying fewer areas of higher sediment yield. Finally, I identified some BMP that could be implemented to lessen the impact from sediment and other NPS pollutants that may occur from increasing runoff due to urbanization in the study area.

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