Estimating and modeling soil loss and sediment yield in the Maracas-St. Joseph River Catchment with empirical models (RUSLE and MUSLE) and a physically based model (Erosion 3D)



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Abstract

In Trinidad the implications of high sediment concentrations in the rivers are becoming a major concern. Three models were used to estimate sediment loads from soil loss due to rainfall in the 41 km² St. Joseph River Catchment. The models were the empirically-based RUSLE and MUSLE for annual and single event loading predictions, respectively and the physically based, Erosion 3D, for single event loading predictions. A hydrologic network was constructed that included an on-line Optical Backscatter sensor (OBS), and a water quality sampler. RUSLE overpredicted the measured sediment yield for the year 2006 seven-fold. MUSLE provided reasonable estimates for rain events greater than 10 mm. For Erosion 3D, estimates for rainfall depths greater than 6 mm were reasonably predicted. For both models, estimates improved with increasing sediment load and rainfall depth.

En Trinidad les implications de la haute concentration de sédiments devient un grand souci. Trois modèles ont été utilisés pour estimer les quantités de sédiments des pertes du sol causé par la pluie dans les 41 Km² de St. Joseph River Catchment. Les deux modèles empiriques ont été RUSLE et MUSLE pour la prédiction d'événements simples et le modèle physique, Erosion 3, utilisé aussi pour la prédiction d'événements simples. Un réseau hydrologique a été construit en incluant un Optical Backscatter sensor (OBS) en ligne, et un échantillonneur de la qualité de l'eau. RUSLE a prédit sept fois plus de sédiments pour l'année 2006 que la valeur réelle mesurée. MUSLE a prouvé être un modèle précis lorsque les pluies atteignent plus de 10mm de colonne. Erosion 3D est considéré précis pour des hauteurs de colonne de plus de 6mm. Les deux modèles deviennent plus précis en fonction de l'augmentation de la quantité de sédiments, et de l'hauteur de la colonne d'eau.

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1. Introduction and Background

Sedimentation continues to be one of the most important threats to river ecosystems around the world. According to the US EPA (2000), sediment is the pollutant that impairs the most stream miles of rivers in North America. The sediment reaching the water systems depends not only on the natural characteristics of the area but also on the anthropogenic influences on the area. The quantity delivered and the transport processes encompassing the sediment source and input depend on the type of land use (Packman, 2000). Cultivated land and livestock trampling (Allan, 2004), forest harvesting (Douglas and Greer, 1993) and urban development (Nagle, 1998) are land uses that act as influential sediment runoff sources on lotic habitats. Sediment intrusions in lotic habitats are generally composed of fine silts and sands that can travel long distances along streams. Sediment loads have multiple effects on most living organisms such as fish, invertebrates and algae (Gard, 2002) and vary in intensity from behavioral to lethal effects on river populations (Newcombe and MacDonald, 1991).

On the island of Trinidad concerns about the implications of the high sediment concentrations found in many rivers have recently focused on efforts to quantify the amount and determine the sources and transport dynamics of sediment in the island's water systems. However, the adverse toxicological effects as well as the impact on water systems of sedimentation have not been investigated on the island. The impact from sedimentation has been mainly corroborated by physical implications such as the clogging of drainage networks, streams and rivers and consequently flooding in urban and rural areas (Figures 1.1.a and 1.1.b).

The Caroni River (Figure 1.2) is the largest river on the island collecting waters from six main watersheds located in the Northern Range and it is of strategic concern due to the proximity of the discharge point of its waters in the Gulf of Paria to the capital city, Port of Spain, and to the fact that its waters drain the Caroni Swamp Bird Sanctuary, the largest RAMSAR site (RAMSAR, 2007) and the largest wetland system on the island.



Figure 1.1.a - Flood event in University of the West Indies in November 13th, 2006. Figure 1.1.b - Drainage network full of debris the day after the flood event.

A feasibility study conducted by the Ministry of Agriculture, Land and Marine Resources of Trinidad and Tobago (MALMRTT) in 1994 focused on the environmental problems affecting the Caroni River Basin in the northern section of the island (MALMRTT, 1994). The study identified ten main causes of watershed degradation, eight of which were known to be major sources of erosion and therefore of sediment delivery to water streams. These were indiscriminate clearing of forest areas, shifting agriculture, forest and bush fires, squatting, cultivation of hill slopes without consideration of steepness and without any anti-soil erosion measures, reckless housing site development, faulty road construction methods and indiscriminate quarrying.

Attempts to determine the sediment yield for the Caroni River Basin have been conducted with the use of the USLE (Universal Soil Loss Equation) by MALMRTT (1994). Other studies performed on different watersheds on the island have used the RUSLE (Revised Universal Soil Loss Equation) equation to give rough estimates of sedimentation (Ramlal and Baban, 2007). USLE is an empirical model developed in 1978 that emphasizes the prediction of soil erosion and conservation planning technology, especially sheet and rill erosion (Lal, 1994).

The Revised Universal Sol Loss Equation (RUSLE) is an updated form of the model developed in 1985 to improve its predictions.



Figure 1.2- Location of the Maracas-St. Joseph River Catchment

Calibration or validation of these calculations with field data is often difficult in Trinidad. The main reason is simply the lack of field data, such as was the case for the study conducted by MALMRTT (1994). Currently, no instrumentation network exists on the island, either on a temporary or on a permanent basis to quantify sediment yields. In addition no attempt has been made to understand the dynamics and characteristics of erosion loss in the Maracas-St. Joseph River catchment. Also, there is no study in the region focusing on the relationship between types of land use and stream sedimentation.

The objective of this investigation is to fill the information gap regarding river sedimentation by establishing an experimental network to measure sediment yields and erosion loss in a representative watershed on the island. The Maracas-St. Joseph River Catchment was selected as the watershed in which to install the network due to, among other things, the availability of a long series of river stage and precipitation records. Equally important is the fact that this catchment experiences severe sedimentation episodes when strong storm events occur due to the environmental impact generated by anthropogenic means. This catchment is also important because it is one of several that contribute a significant volume of sediments to the Caroni River and may have an influence on the physical environment of the ecologically sensitive Caroni Swamp. The findings from this catchment can be replicated in the long term to other neighboring catchments with similar characteristics for quantifying the total sediment load entering the entire extent of the Caroni River.

Initially, an OBS (Optical Backscatter Sensor) capable of measuring suspended sediment concentrations was installed at the outlet of the catchment to measure sediment yields. This was complemented by the installation of a precipitation network composed of four (4) rain gauges located in key sites within the catchment. Independent sampling was also done at two sub-catchments that contributed significantly to sediment loadings; one subcatchment contained a limestone quarry, the other a housing development site. These two land uses were believed to be responsible for major adverse environmental impacts.

Models are important tools for decision-making, planning and policy development (Lal, 1999). Therefore, a model on sedimentation and erosion in the Maracas-St. Joseph River Catchment could help understand the dynamics and causes of this problem, shed new light on its solutions, and assist in the formulation of policies for pollution control. Two main modeling approaches have been covered in this research, namely, empirically-based and physically based models, and comparisons are made of their performance. The first approach is based on relationships among a number of different relevant variables. For instance, a relationship between sediment yield and river stage in the watershed outlet is an empirical black-box type model where only the most important input (stage) and output (sediment load) are included. Such a relation, however, does not provide any insight into factors controlling sediment yields from catchments and hence may not provide the information necessary for decision making for environmental restoration.

RUSLE (Revised Universal Soil Loss Equation) is an empirical gray-box model since it gives some details on the functionality of the erosion process system. For this application, RUSLE was used to estimate the sediment yield due to erosion on an annual basis. This model has been chosen since currently it is the most popular empirical model for watershed erosion estimation. The RUSLE model is based on a simple equation resulting from the product of defined parameters. The application of the RUSLE under current catchment conditions will update the previous estimates found by MALMRTT (1994) using improved precision tools provided by the upgraded RUSLE equation.

The MUSLE (Modified Universal Soil Loss Equation)—a new version of the RUSLE whose purpose is to estimate sediment yield due to erosion loss on a single event basis—was also used to predict the outcomes of 17 chosen storm events with various rain precipitation intensities.

It should be noted that these sediment yield empirical models provide limited information as they do not simulate water and sediment movement and hence have difficulties for universal application; they also have serious size limitations.

Physically based models focus on mathematical equations that describe the laws of conservation of mass and energy and are alternatives to empirical models. In the case of sediment and erosion predictability, they permit higher resolution and enable sediment prediction per single storm. This is an important aspect since one of the findings of this study was that single key storm events of high return periods may be responsible for most of the annual soil loss in a given catchment.

EROSION 3-D is a physically-based model developed in Germany for estimating catchment rain induced soil erosion and deposition as well as runoff for single storm events (Novakova et al, 2005). It is one of several physically-based models but it was chosen as a tool for this project mainly because of its small number of input parameters in simulating soil loss and sediment yield on an event basis. The model is compatible with Geographic Information Systems (Schmidt et al, 1999). The model had previously only been used in European agricultural watersheds so this study provided an opportunity to assess its capability for tropical catchments.

The aim of the study was to estimate and model soil loss and sediment yield in the Maracas-St. Joseph River Catchment with two empirical models, RUSLE, an annual yield model, and MUSLE, a single event model as well as the single event, physically based, spatially distributed model, Erosion 3D. The objectives were as follows:

- To develop a hydrological and sediment measurement network, to provide data for calibration and validation of the models.
- By means of an OBS (Optical Backscatter Sensor), estimate the annual sediment yield of the catchment by measuring individual loadings from a series of storm events.
- To assess the ability of the physically based model Erosion-3D for modelling steep, developing catchments in tropical climates.
- To calibrate Erosion 3D in watersheds with land uses other than agriculture to determine unknown representative values for some input parameters.
- To estimate yields from land uses that make significant contributions to the loadings from a developing catchment.

This reports starts with a literature review in the next section that describes the erosion and soil loss processes, the factors affecting them and their on-site and off-site effects. The use of models for predictions is also described as well as the developments in their applications. The final emphasis is on the models used for this study; RUSLE, MUSLE and Erosion 3D. Section 3 follows with a description of the study site and its geographic location in which the hydrological, soil, topological and land use characteristics of the catchment are mentioned. Section 4 describes the instrumentation used in the project, its setup and installation and the criteria for its location. A description of the calibration procedure for the most relevant equipment is also included. Section 5 describes the methodology followed for sample analysis and the on-site procedures applied to measure stream flow rate, the parameter estimation criteria, the available sources of information and the various assumptions made when selecting the input parameters of the models used in this study. Section 6 covers the field results gathered on-site and after the sample processing in the laboratory. It also describes in detail the calculations performed and the relevant analysis. The final outcomes of each of the three models are also discussed and their results compared to determine their suitability when measuring soil loss in the Maracas -St. Joseph River Catchment. The major findings of the study are listed in Section 7 and recommendations for further work are provided in the last section.

2. Literature Review

The effects of soil loss in agriculture cause a decline in soil productivity characteristics by changing its physical properties, altering its water supplying capacity, reducing its fertility and by increasing its acidity and lime requirements (Harlin and Berardi, 1987). Soil loss in U.S. agricultural fields ranges from 0 to 120 tons per acre per year and approximately 34% of its croplands lose soil at a rate that affects long term productivity substantially (Brown, 1984). In Africa, erosion and desertification have reduced agronomic productivity by 20% (Lal, 1999). The most well known effects of crop erosion include losses in replaceable and irreplaceable attributes of the soil, on-site and off-site sediment effects, release of particles into the air, and gullying. The most harmful off-site effects are the in-stream biological impacts although the effects on navigation and the recreational sector such as swimming and boating accidents and recreational fishing should not be disregarded. Erosion also enhances sediment accumulation in lakes and reservoirs, decreasing their water storage capacity, varying water temperature, and encouraging the growth of water consuming plants. Although it is well known that flooding is not solely due to sedimentation, it does indeed exacerbate the problem (Harlin and Berardi, 1987). Problems such as clogging as water flows through water conveyance systems and increased watertreatment needs and costs (Moehansyah et al, 2004) affect infrastructure and human populations directly.

Water erosion is defined as the removal of soil from any type of land by runoff generated by melting ice and snow, rain or any type of running water (Schwab et al, 1981) or as the detachment or entrainment of soil particles (Lal, 1999).

The factors affecting erosion are soil, topography, climate and vegetation. Properties of soils such as structure, biological and chemical composition, organic matter, texture, moisture content and density directly affect the infiltration capacity of soil as well as its dispersion and transportation. On the other hand, high infiltration rates, higher percentage of organic matter in soil and improved soil structure enhance erosion resistance (OMAFRA, 2007). Topographical features of the land such as slope may have a strong influence on erosion rates. At steeper angles, high flow velocities are generated which in turn enhance erosion considerably. The shape and size of the catchment along with the slope length, defined as the horizontal distance from the origin of overland flow to the point where either the slope gradient decreases enough that deposition begins or runoff becomes concentrated in a defined channel (Renard, 1997) also play an important role in determining erosion rates.

Soil loss is directly linked to climate and its variables such as precipitation. Michael et al (2005) found that due to climate change, the increase in precipitation in Germany in the next 3 decades will generate considerable increments in erosion rates. Regarding climate, the relationships among runoff, erosion and precipitation are complex (Moehansyah et al, 2004) and increases in precipitation parameters such as total precipitation volume and rain intensity do not guarantee proportional increases in soil loss. Attempts to develop proper relationships between erosion and simple precipitation parameters (average rainfall intensity and total rainfall depth) like the depth-intensity distribution developed by Dijk et al (2005) have also proved successful. Erosion rates tend to be not as dependent on the total volume of rainfall as on rainfall intensity and kinetic energy (Nearing et al, 2005). It appears that the best factor to relate climate with erosion and even better than rainfall peak intensity or total rainfall volume is the El₃₀ factor (Renard, 1997). This factor represents the erosive energy of the rain event and is simply the product of the kinetic energy of the storm interval and the maximum intensity happening in a 30 minute interval. Soil loss is enhanced as this factor increases.

Vegetation reduces soil loss by absorbing the rainfall energy of raindrops and reducing runoff, decreasing flow velocities, restricting soil movement by roots and weeds, improving porosity and aggregation and decreasing soil moisture by transpiration (Schwab et al, 1981). Changes in vegetation, soil composition, compatibility, roughness, and soil cover account for the impact of land use on soil loss quantities. Therefore, land use and soil cover play a significant role when predicting soil loss or sediment yields and must always be included in erosion modeling. Land uses which are considered major sediment sources include construction sites, roadway embankments, ditches, cuts, disturbed forest lands, surface mines or quarries, agricultural lands and natural geological eroding "badlands" (Haan, 1982).

Erosion in guarries, agricultural plots and construction sites is high when compared to other land uses due to the high exposure of loose soil to the atmosphere and the interventions on the soil structure. Consequently, the erosion coefficients for these types of land uses are high (RUSLE On Line, 2006; Jung et al, 2004; Lal, 1999). Studies of erosion assessment in guarries and the options to control it have been made by Johnstone and Longworth (1976) for the case of silica sand quarries. Pudasaini et al (2004) found that erosion intensity in construction sites is 10 to 20 times higher than in a normal agricultural plot. This shows that developing watersheds under prominent construction are subject to large erosion problems. Because of this, a considerable number of studies involving erosion prediction and control measures in housing developments, highways and other types of construction sites have been developed with the aid of GIS systems (Parker et al, 1995), rational methods (Miller et al, 1982) and other mathematical models (Warner and Dysart, 1980). Forest areas tend to have low soil loss rates as proven by the low value assigned for cover management factors in different types of empirical (Morgan, 2005) and physical models (Michael et al, 2001). After performing a study on a forested catchment in the United States, Sun et al (1998) predicted that in forests most of the soil loss was produced by poorly managed roads crossing the forest and that soil emission from the forested areas is considered little or insignificant. Erosion is also difficult to predict in these areas since it occurs in patches spread across the area in a heterogeneous manner.

Regarding the erosion process itself, man-made erosion caused by water involves the confrontation of attacking forces that try to remove and transport soil and the retarding forces that do the opposite (Schwab et al, 1981). Erosion starts developing when water droplets fall on unprotected land between rills. Transport of sediment is then initiated towards the closest small rill, then consecutively to larger rills, channels, streams and finally to flowing rivers (Lal, 1995).

The main types of water erosion comprise raindrop, sheet, rill, gully and stream channel erosion (Schwab et al, 1981). Raindrop erosion happens when rain droplets fall on soil or shallow water causing soil loss by splash directly or by increasing water turbulence. Wind, slope, vegetative cover, and surface condition are all factors that condition the soil splash distance and direction. The splash tends to move further downhill than uphill due to the larger traveling distance of soil particles and the favorable angle of impact. The idealized concept of sheet erosion, in which soil is eroded in thin layers, has been recently proved to be oversimplified and inaccurate. Small scale rilling starts simultaneously with the initial removal and transport of soil particles when raindrop impact and surface flow are combined. Rill erosion is derived from this small scale rilling as a concentration of overland flow develops small and well-defined channels. This is the form of erosion where the greatest soil loss occurs. The difference between gully (channels larger than rills) erosion and rill erosion is that rill erosion can be corrected by soil conditioning while gully erosion cannot be corrected by such practices. Also, generally gully erosion is a more developed stage of rill erosion. While gully erosion usually happens in intermittent streams located in the upper regions of stream tributaries, stream channel erosion happens in the downstream end of tributaries. It is composed mainly of soil movement on the bed or soil detachment from stream banks. Erosion from stream banks is due to water flowing over the side or by scouring. Scouring is influenced by channel geometry, soil texture and direction and velocity of flow (Schwab et al, 1981).

The susequent transport of this eroded material in the stream depends on the availability of materials, channel roughness, size distribution, turbulence, velocity of flow, cohesiveness, diameter of sediment and on the presence of any obstructions in the flow. Sediment can be transported in the flow by suspension, saltation and bed load (Chang, 2002). Suspended sediment remains suspended for periods of time without coming in contact with the stream bed and is normally comprised of wash load (i.e. it does not originate from the stream channel). Its velocity and concentration vary with depth and distance from the bed. The saltation load comprises particles that are constantly skipping or jumping along the stream bed, and it is generally considered a part of the bed load. Bed load is the material that rolls or moves along the stream bed as it is pushed by the force of the flow. The sediment yield is the amount of transported material passing through a given cross section of a stream in a given interval of time, generally located at the outlet of a catchment. Since the bed load is only a small percentage of the total sediment yield (as it originates from the stream bed) it can usually be neglected in calculations (Kumar and Rastogi, 1987).

Modeling is a useful tool for erosion scenario assessment that enables the adequate selection of erosion control measures (Moehansyah et al, 2004). Erosion and sediment yield can be predicted by using two main types of models; empirical and physically based models. The first group is based on the identification of relationships between parameters when a robust data base exists. These relationships must be statistically significant. Physically based models consist of the description of processes involved with the help of mathematical equations dealing with the laws of conservation of energy and mass (Morgan, 2005). They integrate both the detachment and transport processes for upstream locations and channels.

The most widely used empirical model for erosion is RUSLE (Revised Universal Soil Loss Equation) which is used to estimate annual yield rill and inter-rill soil loss. An adaptation to use this model on a single event basis is MUSLE (Modified

Universal Soil Loss Equation). Other developed empirical models for tropical areas include), the Pacific Southwest Interagency Committee Method (PSIAC) in 1968, the Flexman Method which is a regression equation (1972) for reservoir design as mentioned by Harlin and Berardi (1987), the Dendy-Bolton Method developed in 1976 for three hundred reservoirs in the United States, the Soil Loss Estimator Model for Southern Africa (SLEMSA) developed in 1978 and mentioned by Morgan (2005) and STJ-EROS model developed for the Caribbean region (Ramos-Scharron et al, 2007) . Despite the availability of such a large number of empirical models, RUSLE was the one chosen for this study because of its widespread use and hence the ease with which information is available for selection of its parameter values for the study catchment. This contrasts, for example with SLEMSA that has been recommended not to be used on catchments outside Zimbabwe owing to a lack of information for its application (Slack, 1996).

With some exceptions, the most recent model development has focused on physically-based models most of which are for agricultural fields and plots. One of the most popular models is CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems) developed in 1980, which evaluates non point source pollution from field plots. Other important models include the AGNPS (Agricultural Non Point Source Pollution) developed in 1985 to evaluate potential problems on agricultural watersheds, the ANSWERS (Aeral Non Point Source Watershed Environment) also used for planning and evaluation of control strategies, the SPUR (Simulation of Production and Utilization of Rangelands) model developed in 1983 for range management, the process oriented model used to replace the USLE for routine assessment; the WEPP (Water Erosion Project), also a model called Erosion 3D developed recently in Germany for agricultural plots, and SEDEM (Spatially Distributed Sediment Delivery Model) developed in 2001 by Van Rompaey based on data from different catchments in Europe.

The EUROSEM, KINEROS, and LISEM models, refer to Morgan (2005), are gaining popularity although there are still problems and issues involving the sensitivity of input parameters and the high variability in the simulations due to the low linearity between erosion and rainfall processes (Nunes et al, 2005). In addition, some models require complicated procedures or a large number of parameters such as WEPP, EUROSEM and ANSWERS in comparison to models such as Erosion 3D, MMF, RUSLE and MUSLE (Moehansyah et al, 2004). Sometimes neither empirical nor physically-based models yield satisfactory predictions of sediment yield such as in a study by Reyes et al (2004) with the GLEAMS, RUSLE, EPIC and WEPP models. Other models have been developed for specific types of land use other than agriculture plots. Such is the case for the model developed by Doten et al (2006) which deals with temperate forests, although its application for tropical forests is still waiting to be tested. A detailed comparison between the latest available physically-based models is described by Shroder (2000).

Although originally used and focused on agricultural plots, the models used in this study were the RUSLE and MUSLE (empirical) and Erosion 3D (physically based models). They are all easy to work with and require only a small number of parameters. The latter is particularly important considering the existing data gap for soil type and parameter information within the study catchment, the St. Joseph River Catchment. Although many of the input parameters used in Erosion 3D have only been estimated for agricultural plots, most of them could be applied to other land uses after making the proper assumptions and calculations or performing field studies for these land uses. Such has been the case for the more predominant land uses in the Maracas-St. Joseph River Catchment (forest, residential areas, quarries and construction sites). There are still cases where it is difficult to measure or even estimate parameter values and so reliance must be made for their estimation on past studies reported in the manual of the model or other associated literature (Shroder, 2007).

RUSLE has been used in many locations and applied to innumerable land uses, but for the case of Erosion 3D, this study is a new attempt at predicting soil loss from a developing catchment in a tropical catchment in which the forest is being replaced by agriculture and housing.

2.1. RUSLE (Revised Universal Soil Loss Equation)

The Universal Soil Loss Equation (USLE) model was developed in 1978 as concerns about soil loss due to agricultural practices increased in the United States. The original research for the study of this empirical model can be traced back to Wischmeier and Smith (1978). Its main focus was to predict soil erosion for conservation planning technology purposes, especially sheet and rill erosion (Lal, 1999). The Universal Sol Loss Equation (USLE) was reviewed and improved in 1985 to create the new Revised Universal Soil Loss Equation (RUSLE) (Morgan, 2005). The generic equation of RUSLE is the following:

$$A = R \bullet K \bullet L \bullet S \bullet C \bullet P$$
 Eq. 2.1

where A is the computed soil loss and is generally given in tonne.ha⁻¹.yr⁻¹, *R* is a factor related to rainfall-runoff erosion given in MJ.mm.ha⁻¹h⁻¹, *K* is a factor related to soil erosion given in tonne.ha.h.MJ⁻¹.mm⁻¹, *L* is the slope length factor (dimensionless), *S* is the slope steepness factor (dimensionless), *C* is the factor related to cover management (dimensionless), and finally *P* is the factor representing the supporting practices applied (dimensionless). For detailed information on these parameters refer to Appendix B.

Among the more relevant improvements included in RUSLE when compared to USLE the following can be highlighted: new R factor distributions for areas in the United States; time variance erodibility in the K factor dealing with freeze-thaw processes; new equations for calculations of slope length in the L factor and

steepness in the S factor; additional sub-factors for the calculation of C factor; and new *P* factors for cropland and rangeland (Jones, 1996).

In recent times, RUSLE has been widely applied to catchments around the world such as in China (Xu et al, 2006; and Zhang et al, 2006), the United States (Fu et al, 2006; Blaszczynski, 1992; and Renard and Simanton, 1990), the eastern Mediterranean region (Abu Hammad et al, 2004), Brazil (Lu et al, 2004), Italy (Onori et al, 2006), Trinidad (Ramlal and Baban, 2007), Australia (Boggs et al, 2001) and Egypt (El Nahry and Saleh, 2005).

RUSLE is presently used for a wide range of applications. Among these applications the most popular are estimations of soil loss from different crops and agriculture practices (Nelson, 2002), (Cullum et al, 2000) and (Mutchler et al, 1994), from landfills (Hotchkiss, 1995), mines (Evans and Loch, 1996), construction sites (Kang et al, 2006) rainforests (Igwe, 2003), grazing areas (Stefano et al, 2000), also for soil type soil losses (Yang et al, 2003), modeling of sediment delivery processes (Stefano et al, 1999), as a base for other sediment yield and loss predicting models (Baja et al, 2002; and Boggs et al, 2001), climate change erosion estimates (Yang et al, 2003), organic compound transport in soil simulations (Starr et al, 2000) and sediment yield estimation for different watersheds (Yitayew et al, 1999; MALMRTT, 1994). Therefore, RUSLE can be applied to a wide range of situations, and when combined with GIS and remote sensing can become a powerful tool for soil loss prediction (Bu, 1999).

It is important to state that RUSLE estimates the soil movement at a particular site instead of the amount leaving a specific land area or catchment (Jones, 2001). Being an empirical model, RUSLE does not take into account runoff or the processes of detachment, deposition or transport of sediment. RUSLE is also focused on determining erosion loss on landscapes where significant overland runoff occurs such as clear land, but was not originally designed for natural forested areas, where no overland runoff occurs or where it is focused and limited

(Jones, 2001). Other types of erosion such as stream bank and gully erosion are not included. Recent efforts have been made to incorporate other forms of erosion into the RUSLE equation such as the one developed in Indonesia (Penning de Vries et al, 1998) where Equation 2.2 was used to estimate the total annual yield Y in tonne.ha⁻¹.yr⁻¹ for a 130,000 ha watershed.

$$Y = A * SDR + Gl + Sb + Rs + L1$$
 Eq. 2.2

In this equation, *A* is the annual soil loss given by RUSLE in tonne.ha⁻¹.yr⁻¹, *SDR* is a Sediment Delivery Ratio, and *GI*, *Sb*, *Rs* and *L1* are gully, stream bank, road side and other forms of erosion respectively in tonne.ha⁻¹.yr⁻¹. These last parameters are difficult to calculate and require complex measuring techniques. Therefore it is uncertain if the addition of these subfactors improves the accuracy of the soil loss estimates in a practical manner.

Although RUSLE is mainly used for annual soil loss estimation and it is not recommended for shorter periods of time (Lim et al, 2005), attempts to explore its application for a single storm event have been performed by Nearing et al (2005) by assigning values for the R and C factors for each event as a calibration procedure. In this case RUSLE showed higher sensitivity in medium sized storms than smaller storms and proved to be more sensitive to land cover than rainfall. An attempt to use monthly R factor values for USLE was developed by Moehansyah et al (2004) by the use of an empirical equation that includes total monthly rainfall, number of rainy days per month and the maximum rainfall in 24 hours as input parameters. All predictions were slightly overestimated.

Regarding accuracy, some studies show that RUSLE overpredicts soil loss when compared to field measurements, especially for low soil loss amounts (Kinnell, 2003). When using RUSLE for sediment yield calculations, the overprediction becomes obvious since it ignores sediment deposition and assumes that all the soil loss mobilized by the rainfall exits the catchment. A simple approach used to

solve this shortcoming is suggested by Lim (2005) and Penning de Vries et al (1998) by means of the sediment delivery ratio (SDR) which is simply the dimensionless ratio between the sediment yield at the outlet of the catchment and the gross erosion for the entire watershed. In 1975, Vanoni determined a relationship given by Equation 2.3 between SDR and drainage area in km² (A in the equation). This relationship was determined from information from 300 watersheds across the globe and is considered as the more generalized method of calculating the SDR ratio (Ouyang, 1997). Two other common equations to get the SDR factor are the relationships proposed by Boyce and USDA-SCS; Equations 2.4 and 2.5 respectively (Adeuya et al, 2005). This approach has been widely used for RUSLE sediment yield predictions. Some applications include the works done by Yitayew et al (1999) and Ramlal and Baban (2007). Adeuya et al (2005) worked with the average SDR value given by these three equations.

$SDR = 0.42 A^{-0.125}$	Eq. 2.3
$SDR = 0.3750A^{-0.2382}$	Eq. 2.4
$SDR = 0.5656A^{-0.11}$	Eq. 2.5

The SDR definition still generates some controversy and its calculation has limitations and raises many concerns (Lal, 1994). For sediment yield applications, the use of SDR decreases RUSLE predictions for sediment yield and may underestimate sediment yields in some cases (Yitayew et al, 1999).

2.2. MUSLE (Modified Universal Soil Loss Equation)

The MUSLE model was developed to take advantage of the tools and developments made on RUSLE, but applied to single storm events. It was combined with runoff models and tested in 26 watersheds in Texas (Ouyang Da, 1997). The *R* factor used in the USLE/RUSLE equation (Equation 2.1) is replaced by a new factor R_W calculated with equation 2.6 (Haan, 1982):

$$R_W = 9.05 (V * Q_P)^{0.56}$$
 Eq. 2.6

where *V* is the volume of runoff in m³ and Q_P is the peak discharge rate in m³/s. The new *A* value (Eq. 2.1) obtained when replacing the R factor in Eq. 2.1 by R_W of Eq. 2.6 is now a sediment yield expressed in tonnes. Channel and gully erosion are not included in this calculation and should be added or subtracted accordingly.

MUSLE has been widely used in many locations and applications throughout the world. When trying to estimate sediment yields from croplands in the United States, a study found that MUSLE overestimated sediment yield from rangelands and underestimated those from croplands (Harlin and Berardi, 1987). In this case, MUSLE predictions were closer to real values than RUSLE predictions using the sediment delivery ratio SDR method. This model is more accurate when predicting sediment yield and also eliminates the need for delivery ratios (Williams and Berndt, 1977). Regarding prediction accuracy, Johnson et al (1985) discovered that for 1,200 rain events in a watershed in the United States MUSLE overpredicted smaller events and underpredicted large events. Some studies for small watersheds, however, have given accurate estimates (Tripathi et al, 2001). Strauss and Klaghofer (2003) found that MUSLE overestimated soil loss in areas with high erosion risk and underestimated in areas with low erosion risk.

2.3. Erosion 3D

Erosion 3D is a physically-based model generally used to calculate watershed or agricultural field rain induced soil erosion and deposition as well as runoff for single storm events (Novakova et al, 2005). Erosion 3D simulates various processes such as runoff generation, the particle detachment generated by raindrop impact or runoff, the transport of this particle in stream flow, sediment deposition, and the routing of this sediment along a stream network (Schmidt et al, 1999). It was originally developed for regional planning as well as impact assessment for both the agricultural industry and the farming community. Erosion 3D and its predecessor Erosion 2D are based on the momentum transfer approach developed by Schmidt et al (1999). This principle states that in order for erosion to occur, the soil resistance of the soil must be exceeded by the erosive impact of rain and flow can therefore be represented by a critical momentum flux (Schmidt et al, 1999).

The program requires three different sets of data; one involving the land relief in the form of a Digital Elevation Model (DEM), another linked to the characteristics of soils, and precipitation information in the form of intensity (mm/min) in any interval of time. The list of input and output parameters is shown in Table 2.1.

Input Parameters	Output Parameters
Relief Parameters	Related to the cross-section of a selected grid element
Digital Elevation Model (DEM)	Runoff
Surface and Soil Parameters	Sediment Discharge
Texture	Grain Size distribution of the transported sediment
Bulk Density	Related to the catchment of a selected grid element
Organic Matter Content	Erosion / Deposition
Initial Soil Moisture	Net Erosion
Surface Roughness (Manning's n)	
Resistance to erosion (critical momentum flux)	
Canopy Cover	
Infiltration Correction Factor	
Precipitation Parameters	
Average Precipitation per interval	

Table 2.1 - Input and output parameters for Erosion 3D model

The model starts by assigning an erosivity value that represents the capability of raindrops to remove soil from the bare surface. An internal cover coefficient reduces the rainfall impact. The soil potential to withstand the erosive impact is derived from the soil characteristics. The infiltration approach is based on the

"Horton overland concept" which states that the difference between the rainfall intensity and infiltration is the total available amount of water at the surface. Therefore, the rainfall excess reduced by surface storage results in the overland flow. This overland flow is then input into the runoff routing process. The overland flow and velocity combined with an erodibility factor yield the capability of the overland runoff to detach soil particles. The total amount of sediment that can be transported is limited by its transport capacity and the amount that is deposited is calculated initially from the sum of the sediment originally eroded by flow and raindrop impact and the sediment input coming from the upstream segment. This sum is then subtracted from the available transport capacity of the overland flow in the land cell being simulated (Shroder, 2000). The sediment routing is derived by a steady-mass balance equation. The program also works with the "lowest neighbour" algorithm for sediment and runoff routing processes and with the Green and Ampt's modified equation for infiltration and rainfall excess calculations (Schmidt et al, 1999). This last equation simulates the temporal changes in the infiltration rate for the duration of a storm.

Since 1995, the catchment version of the model has been used in many situations dealing with a wide range of soils and different land characteristics (Wermer Von, 2006).

The soil loss simulations can be useful when decision making is needed for small to large scale projects dealing with agriculture. Some of its applications involve the simulation of the impact of different agricultural management practices on surface run-off and soil loss, the outcomes of land modification and consolidation techniques on soil loss, and the estimation of pollutants attached to suspended particle matter emitted by agricultural plots (Michael et al, 2001). It can also be used for simulations of longer periods of time (yearly, monthly) comprising a number of multiple events. When comparing Erosion 3D with other single event sediment models, significant advantages dealing with applicability can be observed (Table 2.2).

MODEL	Calculation of transport and deposition	Interface to GIS	Efforts to evaluate parameters	Is the model user friendly and comprehensible documented
KINEROS	YES	-	+++	-
EROSION 3D	YES	YES	++	YES
SHE/SHESED/MIKE SHE	YES	-	+++	-
EUROSEM	YES	YES	+++	-
LISEM	YES	YES	+++	-

Table 2.2 - Single event sediment model applicability comparison (Schob, 2006)

According to Michael et al (2001), there are many advantages when using Erosion 3D. For instance, the modeling approach has unlimited transferability to other situations, single event modeling is permitted, simulations generated by the model contain a high spatial and temporal resolution, sediment particle transport and sedimentation can be simulated for sediment budget estimation, and a detailed parameter database is available for the inputs used by the model based on extended field results for various types of soils and land uses. Last but not least, a limited number of parameters are used and it is compatible with GIS software.

Nevertheless, Erosion 3D has also some limitations (Michael et al, 2001) since it neglects the effect of suspended sediment on runoff or turbulence, it assumes a uniform spatial pattern of rainfall intensity for a given slope, it neglects the soil loss generated by stream flow or intercepted rain, it does not include by default the interception and water storage in the watershed in the program calculations although they can be simulated by adjusting the parameters linked with infiltration capacity, it does not consider the infiltration via macro pores, it does not simulate the vertical changes in the chemical and physical characteristics of the soil, and it does not consider the biological activity, weathering effects on soil structure and the dynamic processes affecting soil structure.

The model has been tested for a number of events in an agricultural area in Saxony, Germany between the periods of 1992 and 1996. Its simulations have therefore been calibrated and validated according to these field measurements.

The soil parameter values required by the program and recommended model developers are also based on these studies.

All the applications of Erosion 3D to date have been performed on agricultural areas across Europe, mainly in Germany (Schob, 2006), Netherlands (Schmidt et al, 1999) and Czech Republic (Novakova et al, 2005). Only a third of the applications of this program have been performed for single rain events, and the areas simulated cover an area ranging from 30 m² to 36 km² (Table 2.3). Schmidt et al (1999) in his studies of an agricultural field in the CATSTOP watershed in the Netherlands found considerable overestimations of soil loss and sediment discharge at the outlet of the catchment. It appears that Erosion 3D predictions tend to be more accurate for simulations involving longer periods of time (Schmidt et al, 1999). No application of Erosion 3D was found for tropical regions or locations outside Europe.

2.4. Model selection criteria and comparison

The selection of MUSLE as the empirical model used for this study was based initially on its similarities with the RUSLE equation used to determine the annual soil loss rates. Most of the parameters used in the MUSLE equation were already calculated for the area of the catchment and the missing hydrological parameters were obtained by measurements on site during the 2006 rainy season. MUSLE has also been tested in various locations around the world and there is a large database for the comparison and analysis of the accuracy of its predictions. It is also very accessible as well as cost free since a GIS software- its major requirement-, ARCVIEW 9.1, was already available for this research. On the other hand, Erosion 3D was selected as the physically based model for various logical reasons. Firstly, its cost adjusted to the project's budget and some of the output parameters agreed with the ones required for this investigation. Secondly, the limitations and information gaps on the soil and land types in the Maracas – St. Joseph Catchment demanded a model that would enable the assumption of

various land and soil characteristics that due to lack of time and funds were impossible to collect. Therefore, the input parameter database available for Erosion 3D presented many advantages.

In summary, Table 2.4 describes the major facts, advantages and disadvantages of using MUSLE and Erosion 3D, and helps understand why these two models were selected and compared.

Location	Size	Time basis	Mean relative deviation (%)
Hoelzelbach/Germany (Engelhardt, 1996)	73 ha	year (mean)	25
Catsop/Netherlands (Schmidt et al., 1999)	42 ha	year 1993	76
Hohenfels military training area/Germany (Deinlein and Boehm, 2000)	41 ha	single event	21
Mistelbach/Germany (Klik et al., 1998)	3 x 15m	year	78
Frankenforst/Germany (Botschek, 1999)	10m	single event(rainfall simulation)	53
Methau/Germany (Schroeder, 2000)	2 x 22m	single event(rainfall simulation)	92
Moehlin/Germany (Hebel et al., 2000)	3 x 10m	Year	35
Laenenbachtal/Germany (Hebel et al., 2000)	3 x 20m	Year	78
Bilovice reservoir catchment/Czech Republic (Novakova et al., 2005)	36km	21 years	21

Table 2.3 - Mean relative deviations between measured and simulated soil losses by Erosion 3D (Schob, 2006)

Table 2.4 – comparison between MUSLE and Erosion 3D Models (Schob, 2006)

	MUSLE	EROSION 3D
ORIGIN	Derivation of the USLE equation and developed by Williams and Berndt (1977). USLE was developed by Wischmeier and Smith (1978) to predict sheet and rill erosion.	Upgrade of the Erosion 2D model developed by Schmidt et al (1999). Erosion 2D was the first version of soil loss prediction software developed by Schmidt et al (1991).
AIM	To estimate the sediment load produced by a single storm based on runoff characteristics.	To estimate watershed or agricultural field rain induced soil erosion and deposition as well as runoff for single storm events
LOCATION AND APPLICABILITY	Tested originally in 778 storm events in 18 catchments in Texas ranging from 15 to 1500 hectares.	Tested originally in an agricultural area in Saxony, Germany between 1992 and 1996
MODEL TYPE	Empirically based model	Physically based model
TIME APPLICATION	Single storm period	Single storm period / Yearly estimate
INPUT PARAMETERS	Volume of Runoff, Peak Flow Rate, Terrain Slope Length (L), Terrain Slope, Soil Erodibility (K), Cover Management Factor (C), Support Practice Factor (P)	Digital Elevation Model (DEM), Soil Properties (Texture, Bulk Density, Initial Water Content, Organic Carbon Content, Erosion Resistance, Hydraulic Roughness, % Soil Cover, Correction Factor), Precipitation.
OUTPUT PARAMETERS	Sediment load	Runoff, Sediment Load, Sediment Grain Size Distribution
COMPATIBILITY WITH GIS	Yes	Yes
COST	Free	Approximately US 1,500
		Momentum Transfer Approach (Schmidt et al (1999) Horton Overland Concent for Infiltration
PRINCIPLES USED	 Empirical equation based on the factors suggested by Wischmeier and Smith (1968) 	 Lowest Neighbor Algorithm for Sediment Routing
		Green and Ampt's equation for Infiltration and Rainfall Excess

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	•	LOW COSI	•	Tign spana and temporal resolution
	•	Limited input parameters	•	Limited input parameters
	•	Has been applied in various regions across the	•	Possible sediment budget estimation
		globe. In areas were it was not originally	•	Available parameter database available for
		developed.		model inputs for various types of soils and land
	•	Large database and history of use		uses.
	•	Can be subject to modifications depending on	•	Includes physical processes.
		characteristics of the region	•	User friendly software
	•	Does not require precipitation, channel size or	•	Low software complexity
		geometry information	٠	Used for various catchments although originally
	•	User friendly and does not require any software		developed for agricultural plot scale
		apart from a normal GIS software (ex, ARCGIS)	•	Enables the understanding of the dynamic of
	•	Optimizes hydrologic model parameters to obtain		sediment and runoff transport in the catchment.
		sediment yield	٠	Does not require channel size or geometry
	•	Does not need an SDR factor multiplication for sediment vield estimates as RUSI F requires.		information.
			•	Software has to be purchased
			•	Has not been tested outside Europe
			•	Manual calibration takes large amounts of time
				and requires constant user data entry.
			•	I ond haringte of model running for large
			•	cong perioda or moder ramming ror raige
	•	Does not include physical processes such as	•	Neglects the effect of suspended sediment on
		infiltration denosition or routing		runoff or turbulence
		Channel and culliv erosion are not included in	•	Assumes a uniform spatial pattern of rainfall
DISADVANTAGES	•			intensity for a given slope,
		Does not enable the understanding of the	•	Neglects the soil loss generated by stream flow
	•	duramic of codiment and runoff transmort in the		or intercepted rain.
		uynannic u seunnent anu tunun nansput m me	•	Does not include the interception and water
				storage in the program calculations
			•	Does not consider the infiltration via macro
				pores,
			•	Does not simulate the vertical changes in the
				chemical and physical characteristics of the soil
			•	Does not consider biological activity, weathering
				effects and dynamic processes affecting soil
				structure

3. Site Description

The Northern Range (Figure 1.2) lies in the northern section of Trinidad, the southern-most island in the Caribbean. This mountain range contains the highest peak in Trinidad (942 m) and occupies in total of 1,000 km² of land ranging from 30 to 1,000 m above sea level (m.a.s.l.) Traversing a distance of 43 km in the Eastern direction, the Caroni River collects water from several tributaries flowing southward from the Northern Range and then discharges into the Gulf of Paria via the Caroni Swamp, located on the north-western coast of the island. Due to anthropogenic interventions on the river's natural course now only a small portion of the discharge reaches the Caroni Swamp.

The St. Joseph River Catchment is one of several catchments that flow into the Caroni River. At a distance of 16km from the island's capital city, Port of Spain, the St. Joseph River Catchment extends from North latitudes 10°39' and 10°44' and West longitudes between 61°23' and 61°26'. Its altitude ranges between 30 and 937 m.a.s.l. The terrain is composed mainly of rugged hills and almost half of the slopes in the catchment range between 20° and 30°. Due to the steep slopes, the only stable crops that can be grown in the catchment are tree crops (MALMRTT, 1994).

The average temperature in the region is 26.6 °C, the mean annual humidity 77.1%, the annual sunshine bright hours are 6.96 h/day and the average wind speed is 115.3 km/day (MALMARTT, 1994).

3.1 Hydrology

The average annual rainfall is estimated to be 1,591.6 mm/yr. The wet season extends from the beginning of June to December while the dry season covers the period from January to late May. The wet season accounts for 84% of the annual

rain. The driest month is March and the wettest periods occur in August and November. (Figure 3.1).The total annual rainfall for 2006 was 1386.9 mm/yr¹, a notably drier year in comparison with the historical average for the catchment. The rain-bearing clouds are mainly from the North East and thus intense rainfall is expected in the eastern highlands of the catchment.

3.2 Topology and Soils

The catchment's topology can be considered as moderately steep, since although its terrain has slopes ranging from 0° to 71° more than 70% of its area is subject to slopes higher than 20° (Figure 3.2). The low slopes are located in the alluvium lands close to the stream network.

The Maracas St-Joseph River flows in a North-South direction and is approximately in the center of the catchment. It receives water from two main tributaries; the Loango tributary penetrating the north-western region of the catchment, and the Acono tributary flowing from the east (Figure 3.3). The northern, upper region of the catchment is covered mainly by primary forests. As the river moves downstream the forests become interwoven with open land patches for residential use and agriculture on a smaller scale. Approximately 85% of the catchment is covered by dense or broken forest, and only 8% has been urbanized (Figure 3.4). The urban areas comprise mainly low density residential housing. The Maracas Village in the West-central region and the St. Joseph residential area are the main urban centers within the catchment (Figure 3.3). Please refer to Figure 4.1 for catchment boundary. Urbanization is mainly focused close to the river's main alluvium areas due to the alignment of the Maracas Royal Road parallel to the river that provides easy access. The Maracas and Acono Valley plains also comprise flat land, which permits ease of construction, and are currently experiencing significant urbanization pressures as shown in the land use map of Figure 3.5.

¹ Information collected in Loango station within the Maracas-St. Joseph River Catchment.

Small scale agriculture in the catchment consists mainly of about 400 hectares of cocoa and citrus plantations, the majority located in the Acono Valley and the eastern borders of the catchment. There are some small scale crops of tomato and pepper spread throughout the catchment. There is evidence of slash and burn practices on the slopes mainly for constructing basic housing units and plots for subsistence agriculture. Cattle areas and grazing fields are not present in the catchment.



Figure 3.1 - % of annual rainfall per month for the Maracas-St. Joseph River Catchment



Figure 3.2 – Slope distribution in the Maracas St. Joseph River Catchment



Figure 3.3 – Aerial photography of the Maracas- St. Joseph River Catchment



Figure 3.4 - Type of Land Use in the Maracas- St. Joseph River Catchment

The soils in the catchment are mainly composed of loams from different geological periods (Figure 3.6). Clays are found in alluvium locations in the north eastern catchment. Limestone reserves are found in the upper part of the subcatchment of the Acono Tributary (north east) and currently there is a quarry extracting these reserves.



Figure 3.5 - Land use map of the Maracas – St. Joseph River Catchment



Figure 3.6 Soil map of the Maracas St. Joseph River Catchment.

4. Experimental Sites, Facilities, & Instrumentation

4.1. Site Selection Criteria

The sites chosen in the St. Joseph River catchment (Figure 4.1) for installing gauging equipment were selected to monitor important information on suspended sediment sources and their dynamics.



Figure 4.1 – Total Catchment boundary of the Maracas- St. Joseph River Catchment.

The total sediment loadings were measured at the river section where the Water and Sewerage Authority (WASA) had already installed a long term river stage recorder. The site has been referred to as the OBS site (Figure 4.2) because of the name of the sediment sampling equipment installed there. This site was the outlet point of the study catchment, its area of 40.1 km² being 91% of the entire St. Joseph River Catchment at the point of its discharge into the Caroni River (Figure 4.1). Therefore, the sediment loadings measured at this site can be regarded as a reasonable approximation for the total sediment loadings emitted by the catchment. The area downstream of this site is mainly composed of highly urbanized plains close to the Caroni River.

Within the time available for the study, two other gauging points could be established that could provide estimates of sediment loadings from two different land uses that were making significant contributions to suspended sediment loadings from the St. Joseph River Catchment. The selection of the sites should have subcatchments sufficiently small to facilitate analysis, and preferably should have only one predominant type of land use besides natural forest cover. All the measuring sites for this study are shown in Figure 4.2.

Since construction sites have been noticed to exist along the catchment, it was thought that this type of land use accounted for a substantial percentage of the sediment loadings generated from the St. Joseph River Catchment. One of the chosen study areas represented a small catchment of 0.14 km² where a Construction Site occupied approximately 20% of its total area. A very small fraction of the sub-catchment was occupied by unplanned housing, but this was in the upper part of the catchment and from the water quality of the flows immediately upstream of the Construction Site, this land use was making a negligible contribution to the sediment loadings. As it was reasonable to assign all the sediment loadings to the Construction Site, this location provided an excellent opportunity to measure erosion yields from this type of land use. The concrete-lined channel draining the Construction Site was an added feature as it provided a controlled, non-eroding stream section in which flow and sediment sampling equipment could be installed. Measurements were taken from the

beginning of the 2006 rainy season (July) to the beginning of October of the same year.



Figure 4.2 - Stream network, rain and sediment monitoring points in the catchment

It was also estimated that a quarry located in the upper eastern region of the catchment was a major source of sediment loading to the St. Joseph River. The gray (limestone) coloured runoff released by the quarry in dry periods and in rainfall events can still be easily identified more than 3 km downstream from where the St. Joseph River meets the Maracas River. After removing the

sediment sampler equipment from the Construction Site at the beginning of October, sampling was done at the Acono WT Site until December of the same year. The quarry is the only type of human land use present upstream of the sampling point. The rest of the subcatchment land cover comprises Upper Elevation Rainforest. The quarry has a total area of 0.15 km² and within its boundaries lie various piles of extracted limestone, a vehicle maintenance workshop and other quarry facilities.

4.2. Instrumentation

The instruments deployed in the field for turbidity, sediment sampling and stage recorders are shown in Figure 4.3.

4.2.1. Turbidity and suspended Sediment Measurements

4.2.1.1. OBS-3 Suspended Solids and Turbidity Monitor

An optical back scatter (OBS) sensor (Figure 4.3.a) is an optical sensor used to measure turbidity and/or suspended solids in real time by the detection of infrared radiation scattered (deflected by water molecules, dissolved solids and suspended matter) at angles between 140° and 165°. It consists of three main units; a high intensity infrared emitting diode (IRED), a temperature transducer and a detector. The IRED emits a beam with a cylindrical cross section (half points are located at 50° and 30° in the axial and radial planes respectively). The specific ranges of the OBS used for this project were 0- 4000 NTU for turbidity and 0.1-5,000 mg/L for mud. The OBS probe had two analogue channel outputs, from 0 to 1 V and 0 to 10 V. This permitted more precision depending on the scale of the sediment concentration measurement. As recommended in the manufacturer's manual, the data acquisition frequency (number of recordings made per second) was chosen as 2 Hz with a burst duration of 30 seconds. The burst interval chosen was 10 minutes and data were recorded only if during this period of time there was a significant change in the mV signal. A GL 500 datalogger was used to store and retrieve data.



Figure 4.3 a), b) and c) – OBS suspended sediment sensor, YSI 6820 stage sensor and 6712 ISCO Portable Sampler (left to right, top to bottom order for figures)

4.2.1.1.1. OBS calibration

A sample of exposed soil was taken from the Construction Site to the Soils Laboratory in the University of the West Indies. This sample was mixed with water forming a heavy sediment solution which was constantly stirred. A black 20 liter container was filled with water collected from the river. The OBS sensor was suspended in a vertical position in the middle of the container along with a constantly moving stirrer. A fixed volume of the sediment solution was added periodically to the container with the OBS sensor by means of a syringe, and turbidity and suspended sediment concentrations were calculated for each sample added. The response analogue output (mV) of the OBS sensor for each sediment concentration was recorded for both available channels. Data were fitted to the polynomial curve of the output voltages and TSS shown in Figure 4.4. A total of 13 sediment concentrations were sampled, starting from a turbidity of 0 NTU to 1000 NTU. This calibration curve was used to convert the readings of the OBS to turbidity and suspended sediment concentrations. Since some peak turbidity values exceeded the 1,000 NTU value, a recalibration was performed for TSS measurements up to values of 9,000 g/m³ (see Figure 4.5). For this last case, the exposed soil sample used for the calibration was collected from various sites in the catchment representing the various types of soil, and then mixed with river water as in the calibration procedure described above.



Figure 4.4. – OBS calibration curve for TSS and Turbidity (July 14th, 2006)



Figure 4.5. – OBS calibration curve for TSS (January 26th, 2007)

4.2.1.2. ISCO 6712 Portable Sampler

The 6712 ISCO Portable Sampler (Figure 4.3.c) is a portable water sampler that can be easily transported between sites. It contains a pump that is activated manually or programmed to automatically retrieve water samples from a flow stream. The sampling interval is chosen by the user as well as the volume of the sample and the trigger for starting the sampling. A carrousel advances bottles based on the set sampling protocol. A datalogger stores the information regarding times, volumes and other relevant information of the sampling periods. The 674 ISCO Rain Gauge was attached to the water sampler and used to trigger the sampling mechanism. It also provided a means of comparing rainfall measured by the other rainfall gauges at the Construction Site and the Acono WT Site. The 750 ISCO Area-Velocity Module was also attached to the sampling event. The level of the flow is measured with an internal differential pressure transducer exposed to the flow in the rear side of the sensor and to the atmosphere through

the cable that connects it to the sediment sampler. The hydrostatic pressure is converted to an analogue signal stored in the data logger. The velocity is measured by the transmittance of ultrasonic sound waves that travel in the flow and are reflected back to the sensor.

4.2.2. Stage and Discharge

4.2.2.1. YSI 6820 Sensor

The YSI 6820 Sensor is a multi parameter water quality monitor (Figure 4.3.b) ideal for spot checking and profiling in lakes, seas and rivers. It is capable of measuring up to 9 parameters simultaneously. The sensor available for the project only measured two parameters; depth and conductivity. Data were sent via telemetry equipment to WASA headquarters, about four km south west of the OBS site. Data were recorded by the datalogger only if the signal rose above a pre-determined tolerance setting. There was no fixed recording time interval.

A delta of 0.16 cm was added to all the raw stage sensor readings analyzed since January 2006 as suggested by WASA personnel so as to adjust the sensor base reference to the real stage values.

4.2.2.2. Current meter

In order to measure discharge flows of less than 1.5 m³/s a current meter was used. It is a simple device connected to a portable electronic display that provides flow velocity readings every 5 s. Using this device for higher flows proved inconvenient due to stability problems and possible rotation blockage problems. With the purpose of assessing the reliability of the current meter a simple calibration was performed in a flume in the Hydraulics Laboratory at the Civil Engineering Department, University of the West Indies. The purpose of this calibration was simply to verify that the current meter was operating adequately. The estimated mean error between current meter readings and calculated velocities was less than 19 % as can be seen in Figure 4.6.



Figure 4.6 – Currentmeter calibration. July 2nd, 2006.

4.2.3. Rain Gauge Network

The available rainfall information for the project was obtained from four raingauges. Three Rainwise Inc. tipping-bucket rain gauges with a datalogger, a ground mount and software were installed at the start of the wet season field study in 2006. These gauges were located in the center and northern areas of the catchment (Table 4.1 and Figure 4.2). The tipping bucket was set to 0.0254 mm per tip. The Loango rain gauge, the fourth rain gauge used in the project, has been in operation since the year 2000. Its information is sent in real-time by a telemetry system to the WASA headquarters. Additional historical rainfall data have been gathered since 1967 with a raingauge at the University of West Indies (UWI) St. Augustine Campus, which is in close proximity to the catchment. This rain gauge records continuous rainfall depths on charts.

Number in Figure 4.2	RainGauge	Coordinates	Location in catchment	Elevation (m.a.s.l)	Installation date
1	Loango	(672943, 1184553)	North-East	97	01/01/2000
2	Construction Site	(674143, 1182280)	Center	74	06/07/2006
3	Las Cuevas	(671961, 1186244)	North-West	237	10/08/2006
4	WASA Intake	(674979, 1183698)	Center-West	95	10/08/2006

Table 4.1 Operaling Nain gauges in the Maracas-St. Joseph Niver Calchinen	Table 4.1	Operating Rair	n gauges in the	Maracas-St. J	oseph River	Catchment
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4.3. Site description and Equipment Setup

4.3.1.OBS station

The OBS station is located below a bridge crossing the end of a straight section of the Maracas River in the lower reach of the St. Joseph River Catchment (Figure 4.7). The width of the river is approximately 7 m, and its flow is restricted in the vicinity of the gauging station by vertical banks of hard rock rising up to approximately 5 m from the bed. At this location, the river is passing though a narrow and fairly deep gorge, when compared to sections downstream and upstream.

Moderate sized housing on steep slopes has been constructed recently on the eastern bank of the river with direct access to the main road. On the west bank, the steep slopes are covered by an 80 m width of vegetation cover which separates it from some housing developments on lands with an elevation of about 30 m above the river bank. A steep paved road less than 50 m upstream of the bridge connects these houses with the main road. The bridge crosses the river flow diagonally. The bridge has a concrete support on its eastern bank that has been subject to scouring. At this location, the river has a baseflow depth of approximately 0.3 m and part of the bed is composed of solid rock. The flow is considerably deeper close to this support, making it a feasible location for the OBS since the depth is always greater than 0.25 m (OBS restriction for adequate operation). Downstream of the bridge the river channel widens and a sand bar forms in the middle of the section there. At baseflow, the flow is divided into two streams separated by this sand bar. The cross section was constantly modified

by the storm events throughout the rainy season. Beyond this reach, the river had a meandering pattern along a more pronounced gorge.



Figure 4.7- OBS Main Site Diagram and downstream view from the bridge at the OBS site

The stage sensor was installed by the Water and Sewerage Authority of Trinidad and Tobago (WASA) in 2005 and has been acquiring data since. It operates with a telemetry station that transmits stage readings at 5 minute intervals to WASA offices located a few km south of the station. A box containing the datalogger for this equipment is located at road level, at 2 m from the telemetry antenna. The box is attached to a steel pipe located in the bridge's inner wall that reaches river bed level. The stage sensor is suspended in a vertical position enclosed in this pipe, with an opening at the bottom that enables water to reach the inside of the pipe and therefore be in contact with the sensor.



Figure 4.8 – Schematic diagram of OBS and stage sensor installation at the bridge site.

The datalogger was protected by the plastic box used to safeguard the stage sensor cabling located between the main road and a Vehicle Workshop approximately 10 m from it. To protect the OBS cable coming from the data logger located at the road level, a 150 mm steel pipe was used attached to the bridge abutment. A pipe elbow was fixed close to the concrete support bank with a straight section of pipe attached that held the OBS probe (Figure 4.8). The OBS probe was located at 40 cm off the bed to avoid damage by rolling objects. By measuring the suspended sediment concentration at this height the assumption that this concentration was present in all the river cross section had to be made for the sediment load calculations. It is known that the sediment concentration varies with depth, but the nature of the OBS, which sweeps out an infrared ray with half points located at 50° and 30° in the axial and radial planes respectively and integrates the reflectance produced by sediments within the ray, provides some compensation for this variation. In order to guard it from damage by floating debris it was inserted within a steel pipe and secured to the pipe's inner wall with a welded O-ring. A window was opened in the pipe to allow the optical section of the probe to be in contact with the flow. This window was large enough to avoid interference with the beam emitted by the probe.

4.3.2. Housing Construction Site

This site was located on the Eastern bank of the St Joseph River near the confluence of the St. Joseph and Maracas Rivers (see Figure 4.2). This is a typical land use within the catchment. It is a site whose infrastructure has been prepared for housing, and in which the vegetation has been stripped. Such lands may stay in that condition for several years, as it is frequently observed in Trinidad and Tobago that land is cleared a long time before actual construction of houses starts. The construction area is a two-hectare piece of land to be used for a future housing project (Figure 4.9). At the time of study no houses were yet constructed thus providing a good opportunity to measure sediment loadings from cleared uninhabited construction sites. All roads were paved at the time of study but 60% of the land lacked proper vegetation cover with sediment and soil exposed.



Figure 4.9 - Housing Construction Site Diagram, Drainage to main channel in Construction Site and Main channel view

An RTU rain gauge was located in the middle of the site. Only a few trees were still standing on this site. By the end of the rainy season small plants and weeds as well as grass patches were covering 30 % of the construction area, with more mature bushes flowering on the steep slopes. Only 20% of the site's runoff is emptied directly into the Maracas River along a small drainage channel on the west side or along the northern slopes of the catchment. The remaining 80% of the runoff generated in the Construction Site routes to a small stream at the southern limit of the catchment. The stream length is 1.1 km from its head upstream to the point where it meets the Maracas River. Three concrete drains channel runoff from the Construction Site to the stream. The natural stream has been channeled along its 500 m reach into the Maracas River with existing houses lining its banks. The houses are separated by less than 10 m from the stream banks. The channel has a uniform rectangular cross section 1.2 m wide and 1.5 m deep. This facilitated the water discharge measurements at the site.



Figure 4.10 – Diagram of the sediment sampler set up at the Construction Site.

The installation consisted of attaching the velocity-depth module to a small steel plate that was leveled into the concrete bed to a depth of 1.5 cm, allowing the velocity-level module upper surface to be level with the bed. This setup did not interfere with the flow (Figure 4.10). The intake tube and module cord were also buried into the concrete bed and covered with steel plates to avoid interferences with the flow. The first sample of the sediment sampler was triggered when more than 0.50 mm of rain fell in less than 15 min.

4.3.3. Acono Water Treatment Plant

The sediment sampler was moved to its second location at the beginning of October and left there until December. The site is located in the upper eastern side of the St. Joseph River Catchment on the eastern side of a WASA water intake that supplies water to the settlements of St. Joseph and St. Augustine (Figure 4.11). An artificial pond developed after the construction of a weir just 15 m downstream of the intake. The weir is at the confluence of the streams from two subcatchments. Sediment deposition occurs behind the weir. The western subcatchment has a total area of 3.7 km² with more than 70 % of its area covered by upper land forest and the remaining land closer to the site covered by abandoned old cocoa plantations presently with low agricultural impact. The neighboring subcatchment consists of an area of 2.9 km² of upper land forest. A 1.6 ha limestone quarry is located 700 m upstream from the selected site. The sediment loadings produced in the quarry are washed downstream by a stream that passes on the western side of the limestone quarry. A main draining channel routes most of the runoff and sediment generated in the quarry to the stream. Programmed sediment discharges from the quarry's retention ponds are released from time to time to clear the ponds at the quarry's facilities. Thus even in times of no rain, there may be a plume of gray coloured water from these releases.

The sediment sampler was located on the eastern bank of this stream 15 m before the convergence of this stream with the neighboring catchment stream (See "sediment sampler location Nr. 1" in Figure 4.11); therefore water coming

only from the quarry's catchment was analyzed. At the beginning of the sampling stages a sample was taken every hour without any triggering conditions to have a general idea of the background total suspended solids (TSS) concentrations. This enabled the recognition of sudden grey water with high concentrations at baseflow probably caused by some periodic flushing of the retention ponds at the Acono WT Site. Afterwards, rainfall measured at a raingauge attached to the water sampler was used to trigger the collection of water samples. The water inlet of the sediment sampler was attached along with the Velocity–Area module to a concrete plate placed in the middle of the stream bed. A second rain gauge established for long-term data collection was installed in a cleared field inside the compound of the water treatment plant, 30 m from the sediment sampler. The second sediment sampler location shown in Figure 4.11 is the site planned to be used in the future to measure the sediment loadings coming from the forested upstream subcatchment where some old cocoa plantations still exist.



Figure 4.11 – Acono WT Site Diagram and Triggering Rain Gauge at meeting point of streams at the Acono WT Plant weir

5. Methods

Field data collection consisted mainly of precipitation, water sampling, stage and flow velocity measurements, stream discharge, stream cross-section surveys, and stream surveys for site location. Water quality testing in the laboratory included turbidity measurement, total suspended solids measurement (TSS), and settled solids. The parameters measured at both the Construction Site and the Acono WT Plant site are shown in Tables 5.1 and 5.2. Samples were processed within 48 hours and were kept in a cool place in the original sealed sampling bottles. Turbidity and TSS measurements were done for all recorded samples; settleable solids were tested only at the Construction Site, for all except the first event of July 27th. For the OBS stations, turbidity and suspended sediment concentrations were taken in real time so no sample processing in the laboratory was required.

Rainfall from the Remote Terminal Unit (RTU) rain gauges located at the Construction Site, the Acono Water Treatment Plant and at Las Cuevas (see Figure 4.2) recorded rainfall intensity in 1-minute intervals for intensities higher than 0.254 mm per minute.

At the Construction Site rain events were measured from late July to early October. For events before August 25, trigger rain gauge, stage and velocity readings were recorded automatically at 15 minute intervals. This interval was subsequently revised to 5 minutes to provide a more accurate representation of the fast response of the subcatchment to rainfall. The sampling mechanism was triggered when at least 0.64 cm (0.25 in) of rainfall was recorded in a 15 minute interval. Once sampling was triggered, water samples were automatically taken from the stream every 10 minutes, one sample being stored in two adjacent bottles on the carrousel. Thus in any storm, a maximum of 12 samples could have been taken over a 2 hr period as there were 24 bottles on the carrousel.



Table 5.1 – Events and variables sampled at the Construction Site.

Table 5.2 – Events and variables sampled at the Acono WT Plant site.

Event	TSS	Turbidity	Flow	Rain
18-Oct-06	\checkmark	\checkmark	~	~
27-Oct-06	\checkmark	\checkmark	\checkmark	\checkmark
1-Nov-06	\checkmark	\checkmark	\checkmark	\checkmark
4-Nov-06	\checkmark	\checkmark	\checkmark	\checkmark
13-Nov-06	\checkmark	\checkmark	\checkmark	\checkmark

Sampling was done at the Acono WT Site with the same triggering conditions. The number of bottles per sample was reduced to 1, sacrificing the settleable solids analysis in order to double the time of sampling. Therefore, 24 samples were taken at the Acono WT Site every 10 minutes, over a 4-hour period.

5.1. Sediment Property Measurements

5.1.1. Turbidity

Turbidity measurements in the laboratory were done for each sample with the assistance of a Hach 2100N Turbidimeter and according to Procedure 2130A (Standard Methods, 1998), 2 samples per water sample. Samples were properly stirred and shaken before being introduced in the Turbidimeter. Afterwards, these two values were averaged. Turbidity measurements were taken for every water sample from the Construction Site and the Acono WT Plant site. Samples were processed within 2 days. If the turbidity value exceeded the limit range of the turbidimeter—the limit was 9,000 NTU—an aliquot was extracted from the original water sample, diluted with distilled water (usually about 50 times) and retested as above. The value obtained was corrected by multiplying it with the dilution factor.

5.1.2. Total suspended solids (TSS)

Procedure 2540D (Standard Methods, 1998) was used as the guideline to calculate the suspended sediment material for samples in the laboratory. In order to measure the TSS per sample, 0.45 μ m filters were used. Two samples were taken from each water sample, and they were later averaged to get the final total suspended solids concentration. For the cleaner samples the volume of sample passing through the filter ranged between 75 ml and 100 ml but for the heavily loaded samples the volume was as low as 5 mL to avoid clogging of the filter. Filters in aluminum recipients were weighed before and after drying at a temperature of 105 °C for at least 1 hour. TSS measurements were taken for every water sample from the Construction Site and the Acono Wt Plant site.

5.1.3. Settleable solids

The Imhoff Cone procedure used was 2540F from Standard Methods (1998). Four available Imhoff cones at the Environmental Engineering Laboratory at the Department of Civil and Environmental Engineering were used. Only one 1000 ml sample was measured per water sample. The reading of settleable solids was done 45 minutes after pouring the sample into the Imhoff cone. This test was generally done within 24 hr of collecting the sample.

5.2. Discharge Measurements

5.2.1. Velocity- Area Method

Discharge measurements were taken at the OBS Station in the downstream section of the St. Joseph River Catchment. For baseflow and low flows, a currentmeter was used and discharges were calculated using the Velocity Area method described in Appendix A. This method was used for flows less than 1 m^3/s as the accuracy of the instrument falls away for larger flows; also, it becomes increasingly dangerous to be in the stream at increasing discharges. At these small discharges, currentmetering was done at 50 cm spacing across the river section at 0.6 of the depth measured from the water surface.

The currentmeter was used mainly at the beginning of the rainy season when river stages were small and close to baseflow and several independent measurements were made over a six month period to adequately define the stage-discharge relation. Higher flows were measured by the sudden injection method described below.

5.2.2. Sudden Injection method

Common salt (sodium chloride, NaCl) was used to measure river discharge via the sudden injection method, described in detail in Appendix A, according to Herschy (1995). Plastic containers each containing a saline solution of 0.2 kg/l concentration were prepared in the laboratory and taken to the point of "injection" and the resulting concentration in the river stream at a point 500 m downstream was measured using a conductivity meter. Sufficient salt loadings must be injected into the stream to ensure that the meter could detect the diluted concentrations. For flows less than 3 m³/s 20 l of the saline solution were used; for higher flows 50 l were used. The computations for converting the conductivity readings to flow discharge are described in Appendix A. A total of 7 discharge measurements were performed to complement the salt measurements previously done in 2004 and 2005 by Rabi Baboolal (thesis currently in progress).

5.3. Model Parameter estimation and processing

5.3.1.RUSLE (Revised Universal Soil Loss Equations)

The digital sources used to model the soil loss with the RUSLE equation were the following;

- A satellite image Ikonos Aerial photograph with 1m x 1m resolution taken in early 2006 for the Maracas–St. Joseph River Catchment area (Figure 3.3).
- A digital map with urban settings, roads and piping for the Maracas-St. Joseph River Catchment area.
- 1:25000 contour maps (Sheets # 13 and 14) from the soil classification survey done for the Northern region of Trinidad by the Lands and Surveys Division in 1972.
- 1:25000 contour elevation map for the Maracas-St. Joseph River Catchment area.

The procedure was as follows: Firstly, the polyline layer describing the elevation contours of the Maracas-St. Joseph River Catchment area rectangle was converted into a feature file in ARCMAP 9.1. With the tool Create TIN form features, a TIN file was created using soft line criteria. Unnecessary grid point records were deleted from the attribute table. The TIN file was converted into a Raster DEM (Digital Elevation Model) with a grid size of 10 x 10 that shows the

elevation range in the catchment. This grid resolution was considered convenient to take advantage of the resolution given by the raster land aerial photometry file.

The imperfections on the new DEM raster file were filled with the FILL command and converted into a new raster file. This raster image was "masked" with a catchment boundary polygon file encompassing the total area of the catchment. In this way, the raster information was limited to the St. Joseph River Catchment with all surrounding information being excluded. Subsequently, the slopes were calculated (in degrees) with the 3D Analyst Slopes option (Figure 5.2).

The flow direction raster showing the direction of flow for each grid cell was generated from the DEM raster file. This last step was required to produce the flow accumulation raster image from the DEM raster file. The flow accumulation raster image shows where the runoff paths are located. The flow accumulation quantity refers to the number of grid cells in the terrain that channel or conduct water to that specific cell. Various flow accumulation values were chosen until the one that most resembled the polyline shape file already available describing the stream network of the catchment was found. Another criterion for adjustment was to follow the recommendation that only a few slope lengths longer than 304.8 m (1,000 ft) should be used in RUSLE (Renard, 1997). The flow accumulation upstream of the grid cell.

Fourteen major subcatchments were selected to represent the Maracas-St. Joseph River Catchment (Figure 5.3). The 14 pour points (subcatchment outlets) of accumulation points were located to divide the catchment into 14 subcatchments. This pour point file was turned into a raster file by the Features to raster tool. The Spatial Analyst-Watershed option in ARCTOOLBOX was used to delineate the St. Joseph River Catchment area and its subcatchments. It was later turned into the polygon layer described earlier to delineate the area of study. In order to calculate the flow length to the main stream network (>100 cells of

flow accumulation), the raster was clipped with a new raster layer that assigned a null value to flow accumulations higher than 100 cells, and a value of 1 to the remaining cells (Equation 5.1).

Setnull ([FlowAccumulation] >= 100, 1) Eq. 5.1

The Spatial Analyst flow length tool was used to create the flow length raster from this last clip and the Flow Direction raster. The few grid cells with slope lengths exceeding the maximum recommended value were automatically reset to this maximum value (304.8 m) as recommended by Renard (1997). This eliminates any distortions from any higher slope lengths that can not be used with the RUSLE equation. In order to make a polyline layer from the DEM modeled stream network, the Raster calculator was used as in the last step, but this time, assigning a value of 1 to the cells that had flow accumulation greater than a value of 100 cells (Equation 5.2).

This new calculated raster grid was turned into a line shape layer with the Stream to feature Tool (Figure 5.1). All relevant raster files were masked to show only the information in the Maracas-St. Joseph watershed polygon.

The calculations for the following RUSLE factors; Slope Length Factor (L) (Figure 5.5), Slope steepness Factor (S) (Figure 5.6), Soil Erodibility factor (K) (Figure 5.7), Rainfall-Runoff Factor (R) (Figure 5.8), Cover Management Factor (C) (Figure 5.4), and Support Practice Factor (P) (assumed value of 1), the equations used and a brief description are provided in Appendix B.



Figure 5.1 – Digital Elevation Model (DEM) for the Maracas Catchment





Figure 5.3 – Subcatchments selection in the Maracas Catchment

Figure 5.4 – C factor distribution for the Maracas Catchment



Figure 5.5 – L Factor distribution in the Maracas Catchment

Figure 5.6 – S Factor distribution in the Maracas Catchment



Figure 5.7 – R Factor distribution in the Maracas Catchment

Figure 5.8 – K Factor distribution in the Maracas Catchment

5.3.1.1. Slope length (L) and Slope Steepness (S) Factors

In order to produce the L-factor raster file (Figure 5.5), raster files were generated for the λ , m, and β factor values by reproducing Equations B1, B.2 and B.3 found in Appendix B into the raster Calculator. The slope length raster file was used along with the slope raster file as inputs for this factor. For the calculation of the S-factor (Figure 5.6) the conditional function "con" was used in the raster calculation to follow Equations B.5 and B.6 taking as input the slope raster file already generated.

5.3.1.2. Soil Erodibility (K) Factor

In order to determine the values of K for the different soils among the catchment area, the Land Capability Survey of Trinidad and Tobago (MATT, 1966) and the soils map (Sheet 14, Soil classification for Northern Trinidad) were used. The parameters required for this factor calculation included: Soil Organic Matter Content; amount of sand % between 0.10 and 2.00 mm; soil structure; and permeability. The information was taken for the layer corresponding to the first 100 mm of soil. The sand percent was determined as the sum of fine and coarse sand. The permeability was determined based on the soil texture survey produced by the USDA and mentioned by Renard (1997). The relevant information for all soil classes was compiled into Tables 5.6 and 5.7. K values (Figure 5.8) were determined by Renard (1997).

5.3.1.3. Cover management (C) Factor

The land use raster file was generated from the 1m x 1m aerial photometry raster of the Maracas-St. Joseph River Catchment. For the few sections under cloud cover, the digital map with the urban settings was used as the main reference instead. The specific land use polygons were digitized in ArcMap 9.1 at a chosen scale of 1:4,000 m since all details could be recognized on the aerial photograph at this scale and the overall view of the surrounding area could still be appreciated. The ERDAS IMAGE® program was used to facilitate the land use digitizing procedure. This program divides the raster cells into categories depending on the light reflection intensity on the land surface. Each different category can be represented by a different color. Since sometimes it is difficult to recognize the different types of vegetation (forest, grass lands, etc) ERDAS IMAGE® "sharpens" the contrast between these categories. The extent of the catchment was represented as a raster divided into 5 levels of reflected light intensity that when overlaid with the aerial photograph became a useful tool for land use classification.

Seven different land use types were categorized by the reflectance method (Figure 5.4) and the accuracy of the results was determined by a ground truthing exercise involving randomly selecting 50 sites on the map and inspecting their actual land type in the field with the aid of a Global Positioning System (GPS). Adjustments were made as required The C-factors for different land uses were taken from the sources previously discussed in Chapter 2. A summary of the utilized values is found in Table 5.3.

Land Use	C Factor	Source
Dense Forest	0.001	Jung (2004)
Broken Forest	0.01	Ramlal (2007)
Grassland	0.08	Jung (2004)
Urban Areas	0.1	Jung (2004)
Citrus Trees	0.2	Ramlal (2007)
Bare land	0.35	Jung (2004)
Crops	0.4	Ramlal (2007)
Quarry	1	Ramlal (2007)

Table 5.3 – C factor values used for the Maracas St-Joseph land use types.

5.3.1.4. Rainfall-Runoff Erosivity (R) Factor

In order to calculate the R-factor for the Maracas-St. Joseph River Catchment, the precipitation information for the four rain gauges used for the project was processed. For all the stations, the storm events with less than 0.5 inches (12.7 mm) of rainfall were omitted from the analysis, unless at least 0.25 inches (6.3

mm) of rainfall fell in 15 min, as suggested by Renard (1997). Renard (1997) also suggests periods of less than 0.05 inches (1.27 mm) in 6 hours to separate storm events. For obtaining the prevailing response (with respect to the erosion-sedimentation process) of the catchment, Renard (1997) advised that the R-factor calculations be based on a 22 year or more time period. In our case, save for the Loango raingauge (see Figure 4.2) which has 6 years of interrupted rainfall data, only data for 2006 were available from the new gauges in the raingauge network. Where data for this year were missing from the new gauges, the Loango raingauge was used to fill in the data gaps using a linear relation established between the Loango station and each of the other 3 stations. This new raingauge network can at this stage only provide estimates of the catchment response in 2006. The University of the West Indies and WASA intend to maintain this network on a permanent basis and so opportunities for determining the prevailing catchment response will eventually be available.

A "macro" coded in Visual Basic was used to process the raw rain information from the four rain gauges and the steps were as follows:

- i. divide the rain information into separate events;
- ii. calculate the total rain, *E* and I_{30} per event based on equations B.6, B.7 and B.8; and
- iii. verify the criteria for separation of storm events suggested by Renard (1997).

The resulting R- factors for the (4) locations are shown in Table 5.4.

	6 month period		2006 year period		
RainGauge	# events with >12.7mm	Total EI30	# events with >12.7mm	R factor (Total El30)	
Las Cuevas	26	5,923	48 '	8.768 '	
Construction Site	17	4,334	31 '	6,415 '	
Acono Water Treat F	32	6,457	59 '	9,558 '	
Loango site	19	3,038	35	4,497	

Table 5.4 – R-factor values for the (4) rain gauges in the Maracas-St-Joseph catchment.

' Linearly Projected values based on Loango site information
These values were included in a raster layer in ARCMAP. To extend these values to the entire Maracas-St. Joseph River Catchment, 4 interpolating techniques were used in the Spatial Analyst tool, namely, Spline, Kriging, Trend and the Inverse Distance Weighted (IDW) interpolations. The most suitable was the IDW as it best described the noted pattern of higher rainfall intensities in the northeastern part of the catchment caused by the Northeast Trade Winds. Furthermore, with the IDW, no negative or out of range R factor values were generated within the catchment area. The resulting distribution is shown in Figure 5.7.

5.3.1.5. Support Practice (P) Factor

All the land uses categorized for the catchment were assigned a value of 1 since no support practice for agriculture was recognized in the catchment.

5.3.1.6. Average soil loss (A) Value

Finally, a raster image for the A value (Figure 6.10 in Chapter 6) was generated by means of the Raster Calculator after using Equation 2.1. Refer to the Results and Discussion section for details.

5.3.2. Erosion-3D

The soil class classification for the soil type used in Erosion-3D is based on the magnitude of the diameter which in turn is based on the KA 4 system classification taken from the fourth edition of the Bodenkundliche Kartieranleitung ("KA 4") and mentioned by Michael et al (2001). The range of values for soils having grain sizes less than 2 mm is shown in Table 5.5. Soils with larger grain sizes are considered to be gravels.

Main textural class	Limit	s of textural subclass [r	nm]
	Fine	Medium	Coarse
Clay	< 0.0002	0.00020 - 0.00063	0.00063 - 0.00200
Silt	0.00200 - 0.00630	0.00630 - 0.02000	0.02000 - 0.06300
Sand	0.06300 - 0.20000	0.20000 - 0.63000	0.63000 - 2.00000

Table 5.5 – Grain size for various textural classes (Michael et al, 2001)

Erosion-3D requires the input of these 9 soil subclasses for each raster unit. Some of these parameters had been previously measured within the catchment as part of the fieldwork of a comprehensive national soil classification about forty years ago (see the Land Capability Survey No. 3, MATT (1966). All the soil class distributions per soil type were taken from this source. As recommended by Michael et al (2001) the entire clay component was included as medium size clay, leaving the fine and large clay files in the attribute table of the GIS with null values. The sand fine, medium and coarse components were also taken directly from the available data. The total silt component was distributed in the ratios according to the size and particle size distributions suggested by Michael et al (2001). The organic carbon content was also taken from the same source for each type of soil.

Some parameters were also estimated based on the available range of values proposed by Michael et al (2001) for each soil type. The mean value of the proposed range was selected. The values were included in new fields in the soil type shape file used for the RUSLE analysis. This procedure was performed for parameters such as soil bulk density and initial moisture content. The erosive resistance was taken from available tables supplied by Michael et al (2001). Since these tables are only used for agricultural land uses, it was estimated that the settling and consolidation of the soil structure "after more than 10 weeks of preparation for crops" (See Table 36 of Michael et al (2001)) was the one that most resembled naturally settled soil in repose. For clay soils, no information was available, so the soil erosivity relation to soil class sketch diagram designed by Michael et al (2001) was used to estimate a multiplication factor of 2 for the erosive resistance from the loam value. These values might be on the low side as

clay is very much less erosive than loams and might account for overestimates of soil loss if there is a lot of clay in the catchment. For further studies of Erosion 3D in Trinidad it would be interesting to analyze the sensitivity of the model to this assumption and it would also be advisable to experimentally determine these erosive resistance values in a future study, once the equipment to do so is available.

Soil cover estimates were taken from Michael et al (2001) for different types of land uses. For the crop land use defined in the land use classification of the catchment, an average between the monthly values for the potato crops was used since this crop is the one that most closely resembles those cultivated within the catchment (tomatoes and pepper). The urban land use soil cover was assumed as 90 % since it seems that a high percentage of this land use type in the catchment is covered either by grass, garden or impervious surfaces, leaving only approximately 10 % of bare soil exposed. Soil cover values of 0% and 20% were used for the quarries and bare land respectively due to the low vegetation cover.

The hydraulic roughness or Manning coefficients were taken from various sources such as Michael et al (2001) and Mays (2005).

The infiltration correction factor was the parameter involving the highest degree of uncertainty since the tables implemented by Michael et al (2001) do not specifically include the soil types present in the Maracas-St. Joseph River Catchment and they were developed for agricultural practices. Estimates for this factor used in Erosion 3D were not found in the literature, so they had to be estimated either from field data or from calibration. For the open land areas present in the catchment, the factor used for fallow land with settled conditions was adopted since it is the crop stage that most closely resembles the grass lands or open lands. For urban areas the default factor value of 1 was assumed since no information was available and due to the limitations concerning lack of equipment in order to perform a calibration to determine its infiltration correction factor (See section 6.5.1 for details). The values selected for all parameters as well as their sources are shown in Tables 5.6 and 5.7.

The precipitation information for the four rain gauges available was converted to average rainfall intensities in mm/min for every 10 min interval by means of a Visual Basic Macro in an Excel spreadsheet. This information was formatted as suggested by Von Wermer (2006) per rain event for calibration purposes. Regarding the relief parameters, the only relief information required was the Digital Elevation Model derived for the RUSLE model in ARCGIS 9.1 and shown in Figure 5.1.

Lan	i Use		Mannin	g's n [s/m	1 _{/3}]		(%)		ntiltration Corr Factor
Dense Forest			V) 6.0	lichael, 2001			100 (Michael,	, 2001)	3.5 (c)
Broken Forest			0.9 (N	lichael, 2001	(100 (Michael,	, 2001)	3.5 (c)
Grassland (Open Land)			0.3 (N	lichael, 2001	(90 (Michael,	2001)	0.5 (e)
Citrus Plantations			0.16 (N	Aichael, 2001	1)		06		3.5 (e)
Residential			0.9 (N	lichael, 2001	(90 (e)		0.3 (e)
Crops			0.09 (N	Aichael , 200	1)		28 (Michael,	2001)	1.5 (e)
Bare land			0.02 ((Mays, 2005)	~		20 (e)		1 (cal)
Quarry			0.02 ((Mays, 2005)	<u> </u>		0 (e)		1 (cal)
Name	Texture	Organic Carbon %	Fine Sand %	Coarse Sand %	Silt %	Clay %	Erosive resistance (N/m²)	Bulk Dens. (kg/m ³)	ity Intial Moist Content (be validation)
La Pastora Series	Sandy Clay	1,6	29	18	4	39	0,016 (e)	1120 (e)	49 (e)
Guanapo series	Sandy Clay Loam	1,8	51	2	22	25	0,008 (e)	1555 (e)	39 (e)
River Estate Series	Fine Sandy Loam	7	52	12	16	18	0,008 (e)	1555 (e)	39 (e)
Santa Cruz Series	Fine Sandy Loam	1,3	57	23	7	13	0,008 (e)	1555 (e)	39 (e)
St. Joseph series	Fine Sandy Loam	0,9	52	4	21	23	0,008 (e)	1555 (e)	39 (e)
Acono Series	Fine Sandy Loam	1,6	49	14	17	20	0,008 (e)	1555 (e)	39 (e)
Anglais Series	Clay	2	32	26	18	24	0,016 (e)	1120 (e)	54 (e)
Maracas Series	Sandy Clay Loam	1,5	42	16	23	19	0,008 (e)	1555 (e)	39 (e)

Table 5.6 - Soil parameters used for the Erosion 3D Simulation based on Land Use.

(e) - Estimated (cal) - Value after calibration

6. Results and Discussion

6.1. Sediment loadings at Construction Site and Acono WT Plant.

A total of 7 events were sampled at the Construction Site between the dates of 20-Jul and 7-Oct, 2006. The parameters collected and their values per sample are shown in Figure 6.1 for the 27th of July event. The remaining events at the Construction Site are found in Appendix D. As can be seen in the figure, there were some occasions when discharge measurements were estimated from the Manning Equation owing to various problems with the velocity sensor:

$$Q = \frac{1}{n} A R^{\frac{2}{3}} S^{\frac{1}{s}}$$
 Eq. 6.1

where Q is the discharge, *n* is Manning's Coefficient of roughness, R_h is the hydraulic radius of the cross section and S is the longitudinal slope. The slope of the concrete channel (3.3 %) was obtained with the use of survey equipment.



Figure 6.1 Results for the 27th of July event at Construction Site

Baseflow was negligible when compared to peak events and was estimated between rainfall events to be about 0.1 L/s. Sediment concentrations for the baseflow were negligible. There was no correlation between instantaneous TSS concentration of the sample and the rain intensity of the 5, 10 and 15 minutes immediately preceding the taking of the sample. This implies that another precipitation parameter needs to be explored to determine a relationship between soil loss and precipitation. As mentioned in Section 2 above, El₃₀ is a parameter widely used in erosion prediction models such as RUSLE and USLE. *El*₃₀ can be referred to as a measure of the erosive potential of rainfall within an event (Renard, 1997). For the Construction Site, El₃₀ calculations were done only for the events having TSS samples. A summary of the important parameters collected is shown per event in Table 6.1. Settled Solids and Turbidity were measured for all events in order to verify the relationship between Turbidity -Settleable solids and TSS values (Figure 6.2). A hardly significant linear relationship ($R^2 = 0.63$) is observed between TSS and Turbidity, whereas for Settleable Solids and TSS the correlation was lower ($R^2 = 0.35$).



Figure 6.2 – TSS vs. Turbidity and Settleable Solids at Construction Site

Site
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20.3 38 2.54 3,424 2.73 2.62 3,184	עווע עווע עוועאנוע ש, אַקאַ ויאַסטאַרט אַק	<u>піп піп ппитіп m⁻ қд/m⁻ 1,000 м и қд</u> 20.3 38 2.54 3,424 2.73 2.62 3,184 19.1 110 0.76 1.127 8.50 8.64 3.007	24.4 39 1.27 - 4.18 3.89 -	3.8 8 1.02 - 7.76 4.26 -	7.1 15 1.02 - 13.17 3.97 -	28.7 172 0.8 2,444 3.09 2.93 7,043	13.0 151 1.8 674 0.75 0.28 2,619	
	20.3	19 1	24.4	3.8	7.1	28.7	13.0	
9-Aug 19.1 24-Aua 24.4	27-Jul 20.3 9-Aug 19.1 24-Aua 24.4	24-Aug 24.4)	31-Aug 3.8	5-Sep 7.1	13-Sep 28.7	5-Oct 13.0	

Table 6.2 - Event results for the Acono WT Plant

Event	Total event rainfall	Event Duration	Max rain Intensity	Total RunOff Volume	Peak TSS concentration	Max Turbidity	Total sed load	E130
	шш	min	mm/min	m ³	kg/m³	1,000*NTU	kg	MJ.mm/ha.hr
13-Oct	2.5	120	0.5	271	1.54	2,248	42	2.9
18-Oct	15.2	180	1.0	4,468	99.37	55,300	136,947	98.3
27-Oct	20.1	* 06	1.3	1,893 *	75.65	36,050	28,611 *	216.2
1-Nov	25.7	120	1.5	4,482	148.80	70,600	196,687	306.2
4-Nov	5.6	160	0.8	2,367	7.76	82,800	90,604	42.9
13-Nov	68.3	* 06	2.5	739 *	61.54	70,500	14,221 *	1670.4
* - Ontohor 27	dmeyold bac	ar 13th avant ir	formation is in	complete sinc	e the equipment was	demonophic method		

October 27 and November 13th event information is incomplete since the equipment was damaged when the runoff peak of the storm was reached.

A total of 6 events were sampled at the Acono WT Plant between 10th October and 15th November, 2006 from which the discharge from the Acono WT Site passes. The parameters collected and their values per sample are shown in Figure 6.3 for the 18th of October event. The remaining events at the Construction Site are found in Appendix E. The extremely high intensity of the events on October 27th and November 13th temporarily damaged the functioning of the sampler, so only partial data were available for these events. The main parameters measured as well as relevant information per event are shown in Table 6.2.



Figure 6.3 Results for October 8th event at Acono WT Plant Site

For flow rate calculations, the area of the cross section was taken as constant, although this approximation was not strictly the case as some alterations in the naturally-lined stream bed could be distinguished after the large events. The mean flow velocity was obtained from the velocity sensor and the discharge determined as the product of the velocity and the cross-sectional area at the location of the sampler.

The variation of the velocity at the section with depth and across the width was captured by the velocity sensor, which is based on the reflectance from particles within the stream that are captured within the ray. The estimation of the mean velocity by the sensor depends on the extent to which its ray covers the entire stream flow and it was probably a good representation as the channel was not very wide. An important source of error was the inability to measure variations of TSS concentrations across the cross-section due to limitations in the sampler. As it was, samples were taken at a fixed depth, but the variation with vertical depths is not known. The extent to which this might have contributed to error could not have been determined; it should be noted however, that the depths were not considerable, the maximum depth being less than 1 m, and so the fixed depth value probably provided a good representation of concentrations. Nevertheless, the variations across the cross-section should be further investigated.

Noting that the EI_{30} might be the best parameter to describe the effects of precipitation on sediment yield in streams, Figure 6.4 illustrates the relationship between this parameter and the total sediment load for the responses at the two sites. It is important to state that the events recorded for both sites are not simultaneous, so each data point represents a unique event. For all the events with similar EI₃₀ values, sediment loads in the Acono WT Plant were higher than at the Construction Site. The 13th October event does not have an equivalent Ei₃₀ value. If available, then the loadings from the Construction Site might also have been lower. Although this result implies higher sediment emissions from the quarry than from the Construction Site, it can also be explained by the difference in the two catchment sizes and therefore the amount of runoff generated at each site. For the Acono WT Plant events there appears to be a sudden increase beyond the smallest event, perhaps suggesting a threshold El₃₀ (between 3 and 40 MJ.mm / ha.hr) that triggers high soil loss and therefore sediment yields. Nevertheless, there are no El₃₀ values in between to determine whether it would have been gradual or sudden. Therefore, more events are needed to confirm this

hypothesis. This behaviour was not observed at the Construction Site. As expected at both sites, high EI_{30} values correspond to high sediment loads. Various regressions were tested to determine the form of this relationship, and the most significant fit was a polynomial relationship passing through the origin ($R^2 > 0.98$) for the Acono WT Plant and ($R^2 = 0.42$) for the Construction Site. Although the red data point on the bottom left hand corner seems isolated, it is already included in the regression line. Additional points would assist in confirming these relationships and the presence of an EI_{30} threshold value. It should be noted that for the Construction Site only four points, i.e., data from four events, could be used owing to problems with the depth-velocity module for the remaining three events.



Figure 6.4 – Relationship between the EI₃₀ parameter and Total Sediment Load for events in the Acono WT Plant and Construction Site.

By relating the peak TSS concentration and the EI_{30} parameter (Figure 6.5), it can be observed that all the TSS concentrations at the Acono WT Plant are approximately 5 orders of magnitude higher than the ones found at the

Construction Site. As mentioned earlier, a limestone quarry is the only land use apart from dense forest and some broken forest present in the Acono WT Plant catchment, while a housing Construction Site is the dominant land use in the Construction Site subcatchment. This implies that the quarry and Construction Site respectively are responsible for a high amount of the soil loss and sediment loads generated in both subcatchments. It can therefore be inferred that the limestone quarry is a key source of sediment in the Maracas St-Joseph catchment when compared with other land uses present in the catchment.

The fact that the nature and material of the channel at the Construction Site is concrete and that the channel is steep (slope = 3.3 %) means that very little if any deposition of sediments occurs within the channel and that the loading measured for any of the rainfall events came entirely from the Construction Site. Almost the entire sediment yield measured in this case came from direct soil losses generated during the rain event.



Figure 6.5 - Relationship between the EI₃₀ parameter and Peak TSS concentration for events at the Acono WT plant and Construction Site.

On the other hand, the yields measured at the Acono WT Plant are not completely due to soil loss due to the last particular rain event but also to the sediment previously eroded in the quarry and subsequently deposited within the channel, either being trapped by the rough, vegetated banks or streambed. Such sediments may be re-suspended by successive rain events and may eventually pass the sampling point. Therefore, the high TSS concentrations at the Acono WT Plant are most likely to be a combination of fresh material derived from the quarry operations along with material deposited in the stream beforehand emitted by the same source.

6.2. Suspended Sediment load estimates

A total of seven (7) sudden tracer (salt) injection experiments and six (6) currentmeter measurements were taken between July and December 2006 to measure discharge. Results from ten (10) sudden injection tracer experiments conducted between 2004 and 2005 were also available and used for the analysis. The derived stage-discharge relation, a second polynomial regression fit, is shown in Figure 6.6. This was critical for the determination of the flow rate, *Q*, from the stage values measured continuously by the WASA stage recorder. It is also very important for sediment loadings which are the product of the concentration and flow rate. In order to estimate the errors generated in the stage discharge curve, the maximum and minimum polynomial lines derived from the measured points were also calculated. These two lines played a significant role in the range of possible annual sediment yield estimations for the catchment. Errors due to the OBS calibration curve are not included since they are difficult to quantify.



Figure 6.6 - Discharge measurements and Stage-Discharge Curve for the OBS station in St. Joseph River 2004-2006

All the signal data recorded from the OBS's data logger between the 1St September, 2006 and February 28, 2007 were converted to TSS values in g/m³ by means of the OBS calibration curve (Figure 4.7). A total of 24 rainfall events were sampled. The baseflow TSS concentration was calculated for each rainfall event as the average of the entrance and exit points of the hydrographs. The resulting baseflow volume was subtracted from the total runoff volume to determine the real runoff due to precipitation. The stage readings were linearly interpolated from the available stage sensor readings to the time intervals used for the OBS suspended sediment readings. The TSS readings that did not agree with the trend in stage level and the sudden changes not linked to any rain event were considered as noise and discarded from the analysis. This noise was either due to the interference of the OBS emissions by some small fish or various pieces of solid waste from nearby houses. These, however, were easily identified as false readings as they occurred on all occasions including during

times of low flow, or were readily distinguished by spikes on an otherwise clearly discernable signal pattern.

In order to calculate the complete annual sediment yield for 2006, the sediment yields for the missing storm events had to be estimated. These storm events comprised the period between January and August 2006 when the OBS was not in operation, as well as sixteen (16) storm events that occurred during the sampling period but were only partially recorded mainly because of battery problems and the occasional removal of the OBS for calibration and maintenance. For the storm events recorded, a regression equation was derived between the river discharge and the TSS concentration (Figure 6.7).



Figure 6.7 – Relationship between TSS concentrations and interval Flow rate for readings at catchment outlet from 09-2006 to 01-2007.

Logarithmic, linear, exponential and polynomial regressions were tried but the first one resulted in the best R^2 value of 0.6. The behaviour of TSS concentrations in the streamflow and its behaviour regarding flow rates were

studied by means of hysteresis loops in order to find a general trend in the behavior during all events between rainfall and sediment. This could be another helpful tool in addition to Figure 6.7 to determine the estimates of rainfall events with missing sediment concentration data, but the analyzed events proved that every event had a unique loop shape. Two of the largest events recorded are shown in Figure 6.8. For most of the events recorded during the year the rate of change in TSS concentration was faster at the beginning of the rainfall than in the receding stages. The highest TSS concentrations could be found either before reaching the peak flow rate (Figure 6.8.a) or at the beginning of the receding hydrograph (Figure 6.8.b). The different location of the peak for the November 13th event is due to the varying rainfall versus time pattern resulting from the two rainfall peaks, while the November 1st event is more typical of a normal rain event that monotonically increases and then decreases.



Figure 6.8 a) – Hysteresis loops for the event of November 13th, 2006



Figure 6.8 b) – Hysteresis loops the event of November 1st, 2006.

The next step was to determine the sediment loads per time interval. The product between flow rate (m^3/s) and TSS concentration (g/m^3) was obtained in g/s and this result was in turn integrated in the specific time interval so as to obtain the total sediment loadings. The estimated value was 8,758 tonne / yr including the estimates for the missing periods, with a maximum value of 20,593 tonne / year and a minimum value of 6,809 tonnes / yr. The most significant 17 measured events of the year are shown later in Table 6.4, Section 6.4 along with their measured sediment yield values.

Again, as mentioned in Section 6.1, taking the measured sediment concentration of the OBS as the average TSS concentration of the cross section is an important source of error. Since the OBS was located at 40 cm from the bed of the river and at a short distance from the left bank, the OBS reading might not be

representative of the average TSS concentration for the complete cross section. Also, the readings depend on sediment size and the calibration might not have been broad enough to take particle size into account. This will be discussed in the section on recommendations for further research.

6.3. RUSLE Annual soil loss estimates

The soil loss estimates (A value) calculated for the Maracas-St. Joseph River Catchment are shown in Figure 6.9.



Figure 6.9 – Soil loss rates in the Maracas – St. Joseph River Catchment

In order to determine the mean area A value, the catchment was divided into 17 subcatchments for which the mean area A value was calculated. Afterwards, a total mean was calculated from these values based on each subcatchment area (Table 6.3). This mean A value was estimated to be 102 tonne.ha⁻¹.yr⁻¹, and when multiplied by the total catchment area (4,086 ha) resulted in an annual soil loss of 420,000 tonne/yr.

Subcatchme Nr.	Mean A (tonne/ha*y	Area ear)	Mean*area	Area*Mean A (tonne/ha*year)	%
1	16.4	417	6.84E+07	1.7	2%
2	46.6	772	3.60E+08	8.8	9%
3	37.5	363	1.36E+08	3.3	3%
4	460.7	307	1.41E+09	34.6	34%
5	75.9	309	2.35E+08	5.7	6%
6	18.5	295	5.46E+07	1.3	1%
7	306.3	12	3.76E+07	0.9	1%
8	49.9	177	8.82E+07	2.2	2%
9	95.7	104	9.96E+07	2.4	2%
10	95.4	380	3.63E+08	8.9	9%
11	149.2	227	3.38E+08	8.3	8%
12	18.6	76	1.41E+07	0.3	0%
13	36.2	109	3.95E+07	1.0	1%
14	127.9	290	3.71E+08	9.1	9%
15	151.3	153	2.31E+08	5.6	5%
16	214.5	49	1.05E+08	2.6	2%
17	545.6	46	2.51E+08	6.1	6%
Total		4,086	4.20E+09	102.9	100%

Table 6.3 - Mean area A value calculations

This value refers to the total mass of soil mobilized within the catchment due to erosion, but is not necessarily the mass of sediment leaving the catchment per year. As mentioned earlier, some sediment is stored within the catchment, or deposited in the beds of the rivers and streams.

The sediment delivery ratio (SDR) value of 0.142 was the arithmetic mean between the SDR predictions of the Vanoni, Boyle and USDA-SCS equations presented earlier in Equations 2.3, 2.4 and 2.5 respectively. It means that

approximately only 14 % of all the sediment due to soil loss in the catchment reaches the catchment's outlet. Thus after application of this factor to the total annual soil loss in the catchment obtained above, the sediment yield predicted by RUSLE becomes 60,000 tonne of sediment / yr, and approximately 700 % higher than the measured sediment yield (8,541 tonne / yr). This overestimation is not surprising since as discussed earlier similar studies using the RUSLE equation with the SDR procedure for sediment yield have overestimated sediment yields.

It is important to note that the C-factor has a strong influence on the A value (soil loss) as demonstrated by Nearing et al (2005). The direct relation between these two becomes evident by noting that on the maps of A (Figure 6.9) and C (Figure 5.4) values respectively, the locations of high A values correspond to high C factors; low A's correspond to low C factors. Thus if the C factor were overestimated, then its reduction may result in significant reductions in the estimated value of A. This dependence was explored by decreasing all C factors by 50 %. This value was selected only for exploratory purposes. Although sediment yields showed a corresponding reduction by half, the A value was still overestimated by 350 %. It is important to recall that the RUSLE equation was validated originally with data collected in catchments located in North America with very different characteristics from this tropical catchment in Trinidad (Renard, 1997). This might be another cause for the over estimation. If the value of the C factor for dense and broken forests was the only one modified, that is a decrease by 50%, the resulting mean A value changed to 46 tonne.ha⁻¹.yr⁻¹ from the average 102 tonne.ha⁻¹.yr⁻¹ calculated previously. If only the guarry C-factor was reduced by the same percentage, the A value would be reduced to 16 tonne.ha⁻¹.yr⁻¹. The same degree of sensitivity, however, was not displayed by changing the remaining land uses, probably due to their low coverage in the catchment and its medium size C factor values. The low position means that these other land uses do not have a significant land coverage in the catchments; and the medium size C factor means C factors not as low as for forests or as high as for quarries (See table B.1 in Appendix B). This sensitivity analysis test points to the fact that further studies on the estimation of C parameters for the catchment should be encouraged to reduce the uncertainty due to parameter estimation.

The estimations done by MALMRTT (1994) predicted a soil loss of 19,000 tonne/yr compared to this study's prediction of 60,000 tonne / yr. Taking into account that both estimates have followed the same procedure, it would appear that the 1994 estimates better represents the sediment yield recorded for 2006. However, the differences in land use in the catchment for that year are not the same as in the present case. In the 1994 prediction, the limestone quarry and various construction sites were not included in the land use coverage and therefore were not included in that total soil loss estimation.

As seen in Figure 6.9, all annual soil losses higher than 8,000 tonne of sediment/ ha.yr occurring in the catchment are located in the limestone quarry inferring that the quarry is responsible for a significant percentage of the sediment yield at the outlet of the catchment. The construction sites, the small agricultural plots around the catchment, as well as the bare land patches also contributed significantly but only in the order of 2,000 tonne/ ha.yr. All areas covered by dense and broken forest have low soil loss rates.

6.4. Single event modeling with RUSLE and MUSLE

Although RUSLE had been initially developed for annual yield estimations, it had been reported in an earlier section that many attempts have been made to use it for sediment loadings from single storm events. There are problems associated with using RUSLE, such as the expected variation of the sediment delivery ratio for each storm as opposed to its often assumed constant value (Haan, 1982), and the varying R factor, which depends on the El₃₀ value. Nevertheless, RUSLE was still applied on a storm event basis, mainly to see to what extent the literature reports of overestimations hold in this study. For each of the storm

events selected, a new R factor was developed comprising only the EI_{30} of the specific event. Therefore, the resulting R factor values per event were considerably smaller than the annual R factor calculated previously. The remaining factors in Equation 2.1 were not modified and an estimate of the A value (traditionally the annual yield) was determined for each event.

As the results in Table 6.4 show, the overestimation becomes even more pronounced when using RUSLE for single event predictions and it is perhaps further evidence of the inappropriateness of using the RUSLE model for single event soil loss prediction.

MUSLE, however, provides a better opportunity to predict sediment yields for single events. As seen in Table 6.4 MUSLE also overestimates sediment yields in almost all of the events validated; however, this was at a significantly smaller scale than RUSLE. Overestimation increases as the total runoff of the event decreases implying that the MUSLE accuracy for the prediction of sediment loads in the Maracas-St. Joseph River Catchment is better for large events (Figure 6.10). If the consideration made by Yang (1996) which states that sediment model predictions between 50 % and 200 % are considered good is followed, then MUSLE is indeed providing reasonable estimates, and can be regarded as a reliable empirical model for estimating sediment loads for storm depths above 10 mm.

Event	Total RunOff (m3)	Peak Flow rate (m3/s)	Preceding dry period (h)	Measured Sed Yield (tonne)	RUSLE sediment yield (tonne)	MUSLE sediment yield (tonne)	RUSLE Predicted / Measured ratio	MUSLE Predicted / Measured ratio
21-Sep-06	70,181	3.1	164	46.9	1,349.5	88.5	29	1.9
23-Sep-06	9,761	1.5	45	4.7	138.2	15.8	29	3.3
7-Oct-06	1,068	1.2	28	1.9	25.2	3.5	13	1.8
8-Oct-06	7,762	1.7	18	1.3	61.9	15.8	49	12.4
12-Oct-06	32,538	4.0	20	22.7	246.6	68.8	11	3.0
13-Oct-06	6,031	2.1	21	6.3	31.2	16.6	5	2.6
24-Oct-06	19,524	2.4	14	11.9	130.5	35.6	11	3.0
28-Oct-06	47,586	2.6	4	37.8	523.3	62.4	14	1.7
1-Nov-06	99,078	12.0	16	152.3	728.1	255.5	5	1.7
6-Nov-06	11,524	1.1	18	3.1	204.3	11.8	66	3.8
13-Nov-06	276,419	31.5	36	845.9	5,662.7	795.9	7	0.0
21-Nov-06	2,550	1.3	80	1.7	31.6	6.4	19	3.8
1-Dec-06	5,922	1.4	32	3.9	13.3	11.1	ო	2.8
10-Dec-06	28,057	2.0	36	15.5	137.3	37.6	൭	2.4
12-Dec-06	21,148	1.2	19	3.2	19.0	18.8	9	5.8
30-Dec-06	4,536	1.0	117	0.7	12.2	6.0	18	8.9
11 Jan-07	24 322	24	10	49.4	99.4	40.3	~	0 8

Table 6.4 - RUSLE and MUSLE predictions for single events

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Figure 6.10 - Overestimation of MUSLE predictions as a function of rainfall depth

6.5. Single event modeling with Erosion 3D

6.5.1. Erosion 3D Calibration

The calibration procedure for Erosion 3D could be divided into two main stages, the first to determine missing key information regarding the input parameters of the model and the second to adjust Erosion 3D to the Maracas-St. Joseph River Catchment conditions by selecting the most adequate combination of input parameters. The first stage was required because parameters for the limestone quarry and the Construction Site were land uses not modeled previously by Erosion 3D and so appropriate values had to be determined. The second stage was done with nine of the seventeen events that could have been used for calibration. It consisted of testing five different combinations of input parameters for Erosion 3D and then selecting the parameter combination outcome that gave the best fit to the measured runoff. Since one of the Erosion 3D input parameters

known as the initial moisture content is different for every rain event, each event had to be calibrated individually by varying its initial moisture conditions. Once the runoff simulated value closest to the measured runoff value was reached, the corresponding sediment yield value was taken as the predicted Erosion 3D sediment yield value. Figure 6.11 describes the complete calibration procedure for Erosion 3D.

The calibration procedure (first part of Figure 6.11) starts by identifying the most sensitive estimated parameters with the highest degree of uncertainty for the Maracas- St. Joseph River Catchment. These parameters are the Infiltration Correction Factor (ICF) and the Initial Moisture Content (IMC). The ICF is required to account for limitations in the Erosion 3D infiltration procedure that does not account for vertical changes in the soil properties, secondary pores caused by biological and physical processes in the soil, nor the dynamic processes that may influence infiltration during a rainfall event. From preliminary trials with the Erosion 3D model, the most sensitive parameter was undoubtedly the infiltration correction factor ICF. Much work has already been done to provide the range of values of this parameter for predominantly agricultural land use. However, little, if any work has been done for estimating its values for construction sites and quarries. Thus the application of the model to this catchment necessarily requires field measurements of sediment loadings and rainfall from plots with these land uses that can assist in the estimation of this parameter value. The TSS and flow rate measurements obtained at the Construction Site and at the Acono WT Site were used for this process. In the Construction Site case only two dominant land uses were found, namely primary forest and bare land, enabling the calibration of a combination of values of this parameter for both land uses. Likewise, there were only two dominant land uses within the Acono WT Site, namely the limestone guarry and also primary forest. For both sites, ten combinations of parameter values for the forest and the other landuse for each catchment were made, as shown in Table 6.5. Each of these represented a feasible parameter set and Erosion 3D simulations were made for each of them.



Figure 6.11 – Erosion 3D Calibration Procedure Flowchart

The objective function for determining the goodness of fit of each combination was the ordinary least squares between the simulated sediment yields and the observed sediment volume, called *VOL*, given by equation 6.4 where v_{SI} is the simulated sediment yield, v_{OI} the observed sediment yield, and *M* the number of events.

$$VOL = \frac{1}{M} \sum_{i=1}^{M} \left(v_{SI} - v_{OI} \right)^2$$
 Eq. 6.4

For the Construction Site, *M* was 2, having data sets from storms recorded on July 27^{th} and August 9^{th} , 2006. For the Acono WT Site, *M* was 3, having storms recorded on October 19^{th} , 1^{st} and 4^{th} November.

The procedure for performing the specific site calibration for the ICF was as follows: The land use, soil type and DEM (Digital Elevation Model) fields were clipped from the overall Maracas-St. Joseph River Catchment to the corresponding subcatchments, along with all the parameter information. One combination of parameter values was chosen for the ICF for forest and for the other predominant land use. The model Erosion 3D was run, and the total sediment outcome and the total runoff volume were recorded. The model runs were repeated nine more times, each time changing the values of the ICF for the land uses. The combination with the lowest VOL value for runoff volume was chosen rather than the VOL for sediment load as the best possible combination of ICF parameters, since the ICF is more directly related to runoff volume than to sediment yield.

The combinations used for the calibration are shown in Table 6.5. Since a different ICF was obtained for the forest land use from each calibration (Construction Site = 1; Quarry = 6), the mean of the two outcomes was chosen as the forest ICF parameter value.

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Table 6.5 - Infiltration Correction Factor (ICF) calibration for quarry, forest and bare land.

Construction Site calibration

Infiltration C	Correction factor						
La	nd Use	July	27th	Augu	st 9th	Ň	OL
bare land (construction site)	forest	run off (m3)	sediment (kg)	run off (m3)	sediment (kg)	Runoff (m6/s2)	Sediment yield (kg2/s2)
0.1	ę	1,588	2,818	521	420	2.05.E+09	4.02.E+10
£	-	2,079	4,395	1,341	1,695	1.97.E+09	3.95.E+10
~	0	1,565	2,728	480	334	2.06.E+09	4.03.E+10
0	+	2,056	4,307	1,305	1,621	1.97.E+09	3.96.E+10
1	9	260	527	45	153	2.15.E+09	4.06.E+10
0	2	1,542	2,652	446	265	2.06.E+09	4.03.E+10
ε	S	1,090	1,522	96	45	2.11.E+09	4.05.E+10
0.5	2	1,577	2,775	502	372	2.06.E+09	4.02.E+10
0.5	5	442	678	71	204	2.14.E+09	4.06.E+10
6	1	1,059	1,419	80	12	2.11.E+09	4.06.E+10
	Measured value	3.424	3.184	1.127	3.007		

Acono WT Plant calibration

Infiltration (Correction factor	r							
La	ind Use	Octob	er 19th	Noven	nber 1st	Noven	iber 4th	^	oL
quarry	forest	run off (m3)	sediment (kg)	run off (m3)	sediment (kg)	run off (m3)	sediment (kg)	Runoff (m ₆ /s²)	Sediment yield (kg²/s²)
<i>~</i>	~	20,610	67,212	41,668	190,333	8,210	14,900	1.7.E+09	1.1.E+10
0.1	с	11,219	63,880	29,143	162,211	4,654	13,948	6.6.E+08	1.2.E+10
-	2	14,823	55,005	33,525	168,075	6,274	11,723	9.7.E+08	1.4.E+10
-	9	3,752	34,338	14,825	91,982	1,537	7,933	1.1.E+08	2.8.E+10
0	0	14,185	39,613	32,791	144,795	5,984	7,783	9.1.E+08	1.9.E+10
S	S	9,187	23,970	26,843	107,207	3,815	3,402	5.2.E+08	2.8.E+10
0.5	2	15,305	61,401	34,009	177,673	6,419	13,840	1.0.E+09	1.2.E+10
0.5	5	5,186	41,655	19,507	138,310	2,024	10,460	2.3.E+08	1.8.E+10
7	-	19,956	54,639	40,929	169,132	7,920	11,072	1.6.E+09	1.4.E+10
6	1	18,375	30,578	38,473	120,232	7,234	4,741	1.4.E+09	2.4.E+10
	Measured value	4,468	136,947	4,482	192,687	2,367	90,604		

Selected combination with the lowest VOL value for run off.

The difference in the infiltration correction factor estimates for forest land use between both sites can be explained by the fact that in the Construction Site subcatchment there was a higher percentage of disturbed forest (approximately 30%) compared to the quarry catchment (approximately 5%) affecting the infiltration rate directly. The approximations made when measuring the flow rate and sediment yields at both sites (See Section 6.1) would also affect the measured values to which the Erosion 3D estimates are being compared. The calibration yielded final values of the ICF of 1.0 for bare land, 3.5 for forests and 1.0 for quarries. This agrees with the values considered as "reasonable" estimates of 1.0 for quarry and bare land and a range of 2-14 for deciduous and coniferous forests suggested after the analysis by Shroder (2007). It is to be noted that these three land uses cover 90% of the land use of the Maracas-St. Joseph River Catchment so the final simulations will depend heavily on how well the parameter values for these land uses have been estimated.

It is important to state that all the Erosion 3D predictions for total sediment load in the Acono WT Plant site substantially underestimated the real sediment load on the site. This may be due to the high fluidity of the bed at that site but more likely mainly due to sediment material eroded in past rain events found in the stream bed that was gradually moving downstream under the influence of new events. In the single event simulations, Erosion 3D is not taking into account this material but only the sediment eroded in the simulated rain event.

Once the ICF values for the unknown land uses were estimated, no input parameters were missing to start the simulations on the complete extent of the St. Joseph – Maracas Catchment. Although not being an input parameter, the Runoff module of Erosion 3D uses an internal factor called the Runoff Storage Coefficient (RSC) that can be adjusted to increase or decrease the storage volume of the runoff film. It has a default value of 1 and its influence on the shape of the hydrograph is therefore considerable. A separate study was done with the largest storm events used in the calibration as mentioned in the middle of Figure

6.11. By examining the simulated hydrographs thoroughly and performing a sensitivity analysis of this parameter, it was found that a value of 2.5 gave the best fit to the observed hydrographs. The visual comparison for two simulations with two different RSC values for the largest storm recorded in 2006 is shown in Figure 6.12.



Figure 6.12 -Sensitivity analysis for the Run off Storage Coefficient (RSC) for the November 13th event

For the following step (middle section of Figure 6.11), a global calibration was executed to find an acceptable combination of values for all the estimated parameters taking into account the fact that some of them had been estimated and that the assumptions already mentioned for parameter selection had been applied. From all the storm events recorded at the outlet of the Maracas-St. Joseph River Catchment, eight (8) events ranging from one of the lowest recorded, October 8th; to the highest on record for 2006, on November 13th, were selected. There was no automatic procedure provided for calibration of the model, so calibration was achieved by a trial and error procedure. Carefully noting how the change of value of each parameter affected the runoff and soil loss (whether it increased or decreased these quantities), combinations of parameter values were selected. The parameter values were varied by between

5 and 10% from their initial values, having previously determined that up to 10% departure was reasonable. It was decided that doing the calibration between these ranges of variability was sufficient since as shown in Table 6.6, the option that gave the closest sediment and runoff estimate to measured values was the one giving a net decrease of 5% on the soil loss value. It is important to state that this 5% net decrease in soil loss does not mean an overall 5% decrease in soil loss but an increase or decrease of 5% on each of the estimated parameters so as to decrease soil loss in general. Table 6.6 shows the structure of all the combinations applied and the best combination of parameters selected. Again, the VOL was calculated according to Equation 6.4 but this time the OLS was included. Erosion 3D returns a non-processed data file with both runoff and sediment yield hydrographs for the duration of the event. The OLS formulation shown in Equation 6.5 is an objective function that was used for evaluating the goodness of fit of the entire hydrograph.

$$OLS = \sum_{i=1}^{N} (q_{SI} - q_{OI})^2$$
 Eq. 6.5

where q_{SI} is the simulated sediment load or water discharge, q_{OI} the observed sediment load or water discharge, and *M* the number of events.

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Calculation
<i>Table 6.6</i> –

_			_		_	_	
ЭL	Sediment yield (kg ² /s ²)	3,4,E+14	7,3,E+15	1,7,E+15	2,5,E+14	3,2,E+14	
V	Runoff (m ⁶ /s ²)	1,4,E+12	5,9,E+13	1,9,E+13	6,7,E+10	7,4,E+11	
OLS	Sediment yield (kg ² /s ²)	12.162	51.246	24.774	9.926	11.330	
	Runoff (m ⁶ /s ²)	811	4.806	2.746	262	633	
	Erosion resistance N/m ²	OEV	OEV - 10%	0EV - 5%	0EV + 5%	OEV + 10%	
	Manning's rougness s/m ³	OEV	OEV - 10%	OEV - 5%	0EV + 5%	OEV + 10%	
	Soil Cover %	OEV	OEV - 10%	0EV - 5%	OEV + 5%	OEV + 10%	
	Infiltration Correction factor	OEV	OEV - 10%	OEV - 5%	0EV + 5%	OEV + 10%	
	Bulk Density kg/m ³	OEV	OEV + 10%	OEV + 5%	0EV - 5%	OEV - 10%	
	Combination	Estimated value	General 10% increase	General 5% increase	General 5% decrease	General 10% decrease	
	Comb Nr.	4	2	З	4	5	

DEV - Original estimated value

More importance was given to the OLS than to the VOL, since having a low VOL does not imply an accurate simulation of the hydrograph. There were some instances where although the final volume difference between observed and simulated variables was small, the simulated hydrograph was significantly different from the observed one.

Once the best combinations of estimated parameters were chosen, a set of 9 new rain events were used to calibrate the Initial Moisture Content (IMC) by an event basis (lowest section of Figure 6.11). Since the IMC is a state parameter, its values were modified in the last stage of the calibration procedure within a - 30% to +30% range of the calibrated values (see Table C.2 based on Michael et al, 2001) so as to improve the simulated runoff volume. The corresponding sediment load for this runoff was considered as the final simulated sediment load value. The final Erosion 3D estimates of runoff and sediment load with this combination are shown in Table 6.7.

_							
					EROSION 3D		
	Event	Total RunOff (m ³)	Measured Sed Yield (tonne)	Simulated Runoff (m ³)	Simulated sediment (tonne)	Initial soil moisture adjustment %	Predicted / Measured ratio
	21-Sep-06	70,181	46.9	72,065	63.92	-27	1.36
	8-Oct-06	7,762	1.3	7,349	0.58	0	0.46
	24-Oct-06	19,524	11.9	20,304	8.42	-4	0.71
	28-Oct-06	47,586	37.8	43,824	64.84	20	1.72
	6-Nov-06	11,524	3.1	11,540	4.12	-25	1.33
	1-Dec-06	5,922	3.9	913	0.00	20	0.00
	10-Dec-06	28,057	15.5	28,018	13.37	-2	0.86
	12-Dec-06	21,148	3.2	1,431	0.04	20	0.01
	30-Dec-06	4,536	0.7	442	0.01	20	0.02

Table 6.7 – Validation results on Erosion 3D predictions for 9 rain events

As mentioned by Schmidt et al (1999), sediment load and runoff volume are highly sensitive to increases or decreases of the IMC. However, when the original simulation underestimated the measured sediment and runoff values and initial moisture content had to be increased, the simulated sediment and runoff were

insensitive to variations in IMC. Such was the case for the events on the 1st. 10th and 30th December, 2006 shown with Figures 6.13-f, 6.13-g and 6.13-h respectively, which were small to medium sized events. It therefore seems that for these small to medium size events Erosion 3D is simulating saturated soil conditions that result in inelasticity to further increases of initial moisture contents. As a general trend, the overall sensitivity to increases in initial soil moisture is lower than sensitivity to decreases in this parameter. The simulated peak flow rate for almost all validation events (Figure 6.13-a, 6.13-b, 6.13-d, 6.13-e. 6.13-f) except the 10th and 30th December events shown with Figures 6.13-g and 6.13-h respectively is reached earlier than in the measured hydrographs. For these exceptions as well as for the 10-08-2006 event (Figure 6.13-b) the simulated runoff peak is barely noticed. There are two possible reasons for this observed inaccuracy in the runoff validation process: (i) the Erosion 3D describes only streamflow and does not model stream runoff or base flow. Therefore, the program does not require stream bed geometry such as stream cross sections as input parameters; (ii) the reported limitation of the infiltration process for large events occurring after long dry spells (Werner Von, 2007).



Figure 6.13 a) and b) - Runoff Validation events for various Erosion 3D (08-21-2006 and 10-08-2006)



Figure 6.13 c), d), e), f), g) and h) - Runoff Validation events for various events with Erosion 3D (10-24-2006, 10-28-2006, 11-06-2006, 12-01-2006, 12-10-2006 and 12-30-2006 respectively)
6.5.2. Erosion 3D and MUSLE estimates comparison

The comparison between the predicted sediment loads by MUSLE and Erosion 3D and the measured values per rain event is shown in Figure 6.14. All events of the Initial Moisture Calibration are included in the graph, while only the largest events of the Estimated Parameter Calibration are shown. These last events are shown for comparison purposes since they involve the significant large events.



Figure 6.14 - Comparison of MUSLE and Erosion 3D predictions against measured values

As mentioned earlier, MUSLE overestimates sediment loads for almost all events except for two of the three largest events. There is a clear convergence of the estimated values towards the measured values as the sediment load increases. For events between the range of 1,000 kg to 10,000 kg, MUSLE has a better estimation than Erosion 3D. Erosion 3D completely underestimates sediment

loads for the smallest events, although this is directly linked to underestimates of runoff in the runoff model. It appears that Erosion 3D can be a better tool for predicting sediment load estimates for events higher than 10,000 kg., but its reliability falls away for events with decreasing sediment loads. Figure 6.15 shows the relationship between sediment values (measured and predicted by Erosion 3D and MUSLE) and rainfall depth. It can be seen that for events with rain depths greater than 10mm, Erosion 3D predictions fall within the error ranges. Again, based on the criteria developed by Yang (1996) which states that sediment model predictions for events larger than 6 mm of rain depth are considered accurate estimates. Total sediment load generally increases with total precipitation showing how sediment yields in the main stream are linked to soil loss due to rainfall.

Figure 6.15 also shows that for large events, all MUSLE estimates fall in between the error limits of the measured values while for small events this does not happen. This is encouraging and points to the potential of MUSLE for predicting sediment loadings from large storm events. These good estimations for large events would therefore contradict with Strauss and Klaghofer's (2003) underestimations for high soil losses events. On the other hand, it agrees with the findings by Johnson et al (1985) where the more accentuated overestimations corresponded to small events and as the rain event increased predictions moved closer to measured values or even underestimated them.

Objectively, the results given by both models do not show much separation and their predicting capability of sediment yields due to soil loss is similar for this type of application. Therefore, either of the two models could be used for this type of analysis. Nevertheless, MUSLE required less time, data processing and proved to be more user-friendly, while with Erosion 3D, the estimation of input parameters, the development of a proper calibration and the time required by the software to process each simulation were evident drawbacks.





Conclusions

Soil loss emissions in the Maracas- St. Joseph River Catchment appear to be linked strongly to the type of land use involved. For instance, all annual soil losses higher than 8,000 tonnes of sediment/ ha.yr occurring in the catchment are located in the limestone quarry inferring that the quarry is responsible for a significant percentage of the sediment yield at the outlet of the catchment. The construction sites, the small agricultural plots around the catchment, as well as the bare land patches also contributed significantly but only in the order of about 2,000 tonne/ha.yr. No area covered by dense and broken forest has soil loss rates greater than 1000 tonne/ha.yr.

Suspended sediment estimates performed at the outlet of the catchment also showed that the largest event recorded in 2006 was responsible for 10% of the total annual load estimated for the catchment. This implies that further research to understand the relationship between soil loss due to rainfall and sediment loads in the Maracas-St. Joseph stream network should be conducted for large rain events.

Three models were used to estimate sediment loads from soil loss due to rainfall in the Maracas-St. Joseph River Catchment. The two empirically based models were RUSLE (The Revised Universal Soil Loss Equation) for annual estimates and MUSLE (The Modified Universal Soil Loss Equation) for single event predictions. RUSLE overpredicted by a factor of 7 the measured sediment yield for the year 2006, which had been estimated to be 8,758 tonne/yr. This overestimation can be due to problems when implementing the RUSLE parameters for tropical and steep catchments with the characteristics of the Maracas-St. Joseph River Catchment. Although a proper sensitivity analysis of all factors in the RUSLE equation for the Maracas-St. Joseph River Catchment should be performed to adequately discuss the relationship between each factor and the total soil loss or sediment yield, the similarities between the soil loss geographical distribution along the catchment and the distribution of the Cover Management Factor (C Factor) suggest the strong effect of this factor on soil loss.

Following the suggestion made by Yang (1996) which states that sediment model predictions between 50% and 200% are considered as reasonably accurate, it can be concluded that MUSLE is an accurate empirical model to estimate sediment loads for rain events in this particular catchment for events with rainfall depths above 10mm. With the exception of two events, MUSLE more than doubled the sediment loads of a few events but its predictions became more accurate as the event sediment loads and runoff volume increased.

On the other hand, Erosion 3D underestimated events of less than 10,000 kg of sediment yield or rainfall depths less than 10 mm. This prediction error is directly linked to underestimations of the event runoff volume. As with MUSLE, estimates became more accurate as the sediment load and rainfall depth increased. Erosion 3D's estimates of sediment yield can also be considered as accurate for events larger than 10,000 kg of sediment load or above 6 mm of rainfall depth since the estimated sediment loads fall within the range of 50% to 200% of the measured sediment load.

Since Erosion 3D and MUSLE seem to achieve a similar accuracy for sediment load predictions for rainfall depth events higher than 10 mm and since the ratio of simulated to measured values of both models are fairly comparable, it can be concluded that for the Maracas St- Joseph catchment both models are useful. Nevertheless, Erosion 3D estimation and calibration procedures required a considerable amount of time that if applied to neighbouring catchments would have to be repeated. Therefore, MUSLE appears to be a simpler and more user friendly tool to estimate sediment loads. Aside from assisting in the estimation of sediment loadings in the Maracas-St. Joseph River Catchment, the sediment and runoff data gathered with the hydrologic and sediment network was also useful to calibrate and determine unknown input parameters such as the Infiltration Correction Factor (ICF) for land uses different from agricultural uses in Erosion 3D. These factors were estimated to be 1 for quarries and bare land areas and 3.5 for tropical forests.

The next step in the calibration process in Erosion 3D showed that the best overall sediment yield estimate was accomplished when the corresponding estimated parameters (soil cover, infiltration correction factor, manning coefficient and erosive resistance) were increased or decreased by 5% to achieve an overall decrease in sediment load. This combination gave the lowest OLS and VOL objective function values, and therefore was the combination used for the last stage of the calibration process.

Recommendations for Further Research

For future studies linked to this investigation, a special focus on other types of land uses such as residential areas and forest should be performed in order to understand the hydrologic and soil loss mechanisms and quantify their sediment emissions. The stage, precipitation and sediment concentration data base should be expanded in order to be able to validate the RUSLE model with a longer period and to collect more rainfall events to validate MUSLE and Erosion 3D on site. This will enhance the knowledge of the functionality of these two models to measure soil loss and sediment loads in steep, tropical catchments with various land uses such as the Maracas- St. Joseph River Catchment.

Regarding the RUSLE predictions, a proper and extended sensitivity analysis of this model should be performed to discover the nature of this overestimation. This analysis was not performed in this project due to time limitations and since it was not covered by its scope, although it should be encouraged for future research. Although Michael et al (2001) performed a sensitivity analysis for Erosion 3D for most of the input parameters used in the software for conditions in Europe, a separate sensitivity analysis should also be performed for tropical watersheds since many land use, land cover and soil characteristics differ from the ones found in European agricultural watersheds. This would enable an estimate of the error range of its predictions for tropical catchments.

Regarding the instrumentation used to measure flow rates and sediment concentrations it is advised that in the following stages of this project, the ISCO 6712 Portable Sampler should be replaced by an OBS with an attached pressure and velocity transducer to measure flow rates. The velocity-depth module attached to the Portable Sampler presented many failures and operating problems. Besides, the extensive laboratory procedures for sample analysis of only TSS concentrations could be easily replaced by an OBS sensor with real time measurements of suspended sediment concentrations.

Regarding the calibration of the OBS, accuracy could be improved by making a real time correlation by operating the Portable Sampler sediment sampler and OBS at the same location. The Portable Sampler would collect samples at defined time intervals while the OBS would record sediment concentrations. Thus, a real-time calibration with real river samples would be performed. This procedure would avoid calibrations made in the laboratory with artificial sediment samples that might not adequately represent the sediment in the Maracas River.

Finally, it would be interesting to see how well Erosion 3D predicts long term sediment yield for the Maracas- St. Joseph River Catchment since this option is available in the Erosion 3D software. However, this analysis was not preformed in this study due to the long time taken for this simulation and the rainfall information missing for part of the dry period of 2006.

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Appendix A – Flow Rate Measurement Procedures

A.1. Velocity-Area Method (Mean Section Method)

Materials required: Current meter, Current meter pole, distance meter, notebook, waders, boots, umbrella, stage recorder.

- The ideal cross section is selected and required materials are arranged on site.
- The present stage level of the flow is recorded.
- A distance meter is laid across the river from bank to bank. Between 20 and 30 points for vertical profiles are selected at approximately equal spacing.
- The current meter is adequately installed in the current meter pole in order to start measurements.
- Starting from one bank, the water depth and the velocity are measured. Ideally, several points along the vertical profile should be selected for velocity measurement, but due to the intermittent characteristics of the Saint Joseph River, a representative point located at 0.6 of the depth from the surface was measured. The discharge passing through a segment between two of the measured verticals is given by Equation A.1., where

$$q_{2-3} = \left(\frac{\bar{v}_2 + \bar{v}_3}{2}\right) \left(\frac{d_2 + d_3}{2}\right) (b_3 - b_2)$$
 Eq. A.1

 q_{2-3} = discharge through segment 2-3. v_2 , v_3 = mean velocities in verticals 2 and 3. d_2 , d_3 = depth of flow at verticals 2 and 3. b_2 , b_3 = distance from an initial point on the bank to verticals 2 and 3. • The same methodology is used for all segments, and finally the total discharge of the cross section is the sum of that for all segments.

A.2. Sudden Injection with salt Method (Integration Method)

Material required: Salt solution containers, salt, stage recorder, conductivity meter, cell phone, note book.

- The salt concentration solution is prepared previously in the laboratory taking into account that 0.2 kg of salt per m³/s of discharge is considered sufficient for low background water conductivity. The solution should have no more than 2.5 kg of salt in 10 Liters of water. 3 Containers of 10 liters of solution each should be taken into the field for 3 complete measurements on site.
- The cross section for measurements is selected and required materials are arranged on site. The distance between both cross sections should be enough to guarantee the complete mixing of the salt solution in the flow. The following empirical equation for the mixing length L should be validated:

$$L = bQ^{1/3}(m)$$
 Eq. A.2

- Where Q is the stream discharge in m³/s and b takes a value of 14 for midstream injections and 60 for injections from one bank.
- Salt concentrations are previously measured upstream and downstream to register the background salinity level with conductivity meter. The same applies for the salt solution on site.
- The water level is measured downstream.

- The salt solution is injected in the stream and time (t_i) is registered by personnel upstream. Personnel downstream are informed immediately.
- Personnel at the downstream cross section register the time in which the salinity increases above the background level. This time is also recorded as (t_o). It is convenient to verify that the same salinity concentration applies to the entire cross section.
- Salinity concentrations are measured and recorded every 30 seconds until the concentrations return to the original background levels. This time is recorded as (t_f) and (t_f – t_o) is taken as the time T of passage of the tracer.
- The average of salt concentrations through period T is calculated.
- The discharge is calculated using equation A.3, where V₁ is the volume of injected solution, C₁ the concentration of tracer in the injected solution, and C₂ as the average concentration of all conductivity meter measurements:

$$Q = \frac{V_1 C_1}{T \overline{C}_2}$$
 Eq. A.3.

Appendix B – Rusle Parameter Description

B.1. Slope Length Factor (L)

The L factor is defined as "the ratio of soil loss from the field slope length to soil loss from a 72.6 ft length under identical conditions" (Jones, 2001). The L factor can be calculated with Equation B.1 were λ is the slope length; m is a variable slope-length exponent. The Slope length is referred as "the horizontal distance from the origin of overland flow to the point were either 1) the slope gradient decreases enough that deposition begins, or 2) runoff becomes concentrated in a defined channel" (Renard, 1997).

$$L = \left(\frac{\lambda}{22.1}\right)^m$$
 Eq. B.1

The *m* exponent is expressed in terms of the ratio of flow erosion (rill) to raindrop impact erosion (interrill erosion) by Equation B.2. β is expressed in terms of the slope angle in radians (Equation B.3) for soils susceptible to both types of erosion previously mentioned.

$$m = \frac{\beta}{1+\beta}$$
Eq. B.2
$$\beta = \left(\frac{\sin\theta}{0.0896}\right) / \left(3[\sin\theta]^{0.8} + 0.56\right)$$
Eq. B.3

B.2. Slope steepness factor (S)

The Slope Steepness Factor (S) is known as a soil loss ratio between the quantity produced by the field slope gradient conditions and from a 9 % slope with identical conditions. Its value can be calculated with Eq B.4 and Eq. B.5, the last assuming no relationship between runoff and slope steepness.

$S = 10.8 * \sin \theta + 0.03$	when slope is $< 9\%$	Eq. B.4	
$S = 16.8 * \sin \theta + 0.5$	when slope is >= 9%	Eg. B.5	

B.3. Soil Erodibility Factor (K)

The K or the soil erodibility factor is linked to the causes of soil loss due to storm events and is related to soil properties. In other words, it is the rate per precipitation erosion index at which soil loss occurs. The most common source for this factor is the soil-Erodibility nomograph suggested by Renard (1997) which takes as inputs 5 soil parameters: percent modified silt (0,002 - 0.1 mm), percent modified sand (0,1 - 2 mm), percent organic matter and structure and permeability type. Approximations of this nomograph have resulted in applicable equations such as the ones suggested by Renard (1997) which deal with the same or similar parameters. Procedures to calculate a composite LS factor have been also developed by Desmet and Govers (1996), although for this particular study these factors were treated separately.

B.4. Rainfall-Runoff Erosivity Factor (R)

The R factor or Erosion Index refers to the effect of raindrop impact on erosion and quantifies the quantity and rate of runoff linked with a specific rain period. It has been proven that when other parameters are held constant, soil erosion on cultivated land is directly proportional to a storm parameter which is included in the R-factor calculations: the EI_{30} parameter. The EI_{30} of a storm refers to the product of the total storm energy (E) and its maximum 30 minute intensity (I_{30}). This factor is considered to accurately represent the erosive potential of a storm and includes the effects of rare strong rainstorm events as well as the more usual moderate ones (Renard, 1997). Equation B.6 is the most widely used equation to calculate the unitary energy (e_m) per millimeter and was chosen after a rigorous analysis on idealized intensity distributions. The rain intensity i_m is in mm.hr⁻¹ and e_m in MJ.ha⁻¹mm⁻¹.

$$e_m = 0.29 \left[1 - 0.72 e^{-0.05 i_m} \right]$$
 Eq. B.6

The sum in a storm period of all the products of e_m and i_m per gauge reading gives the total E value for the storm as shown in Equation B.7 for interval m, where p is the total number of intervals in the selected storm event.

$$E = \sum_{m=1}^{p} e_m \bullet i_m$$
 Eq. B.7

Finally, the *R* factor (Equation B.8) is then the average annual sum of all the EI_{30} for a given location calculated by using Eq. B.8 for storm *i*, where *j* is the number of storms in an N year period.

$$R = \frac{\sum_{i=1}^{j} (EI_{30})_{i}}{N}$$
 Eq. B.8

B.5. Cover Management Factor (C)

This factor describes the effects of crops and management practices on soil loss rates. It is therefore widely used for conservation practices assessment (Renard, 1997). It can also be defined as "the ratio of soil loss from an area with specified cover and management to soil loss from an identical area in tilled continuous fallow" (Jones, 2001). The *C* factor is calculated with Equation B.9 where *SLR* is the sediment loss ratio for a period *I*, *EI* is the % of the annual *EI* occurring in that period, *EI*_t is the sum of the *EI* values for the n periods comprised (Renard, 1997). The *SDR* is calculated with Equation B.10 (Renard, 1997) where *PLU* is the prior-land-use subfactor, *CC* is the canopy- cover subfactor, *SC* is the surface

cover subfactor, *SR* is the surface roughness subfactor, and SM the soil moisture sub-factor.

$$C = \frac{(SLR_1 \bullet EI_1 + SLR_2 \bullet EI_2 + SLR_n \bullet EI_n)}{EI_i}$$
Eq. B.9

$$SLR = PLU \bullet CC \bullet SC \bullet SR \bullet SM$$
Eq. B.10

The calculations for these subfactors is rather complex and requires precise and detailed data for the area investigated. When such data are not available, C-factor values linked with the type of land use can be taken from previous studies (Ramlal and Baban, 2007). Such a custom is used presently in many RUSLE applications world wide (Jung et al, 2004), RUSLE ON LINE (2006), Ramlal and Baban (2007), MALMRTT (1994) and Lal (1999). It is observed that the values for same type of land use vary from source to source, so special care should be taken (Land use definition, source of factor estimation) when applying these factors.

B.6. Support practice factor (P)

The P-factor in the RUSLE equation accounts for the effect on soil loss due to specific support practices and the contour tillage effect. The support practices often used on cultivated land comprise strip cropping and buffer strips, terracing, subsurface drainage and contouring (Renard, 1997). In other words, it is a ratio between soil loss generated by a specific support practice and the corresponding erosion with straight-row upslope and down slop tillage. The purpose of tillage as an agricultural practice is to incorporate plant residues, fertilizers, to help with soil and water conservation and to prepare seedbed and control weeds. While primary tillage inverts the soil profile completely, secondary tillage does it but only in a partial way. One of the drawbacks of tillage practices is the susceptibility to soil erosion. Thus, the calculations of the P-factor depend directly on the agricultural practices used in the catchment and they need detailed information

on the support practices used on site such as ridge height, slope changes, shear stresses, etc. For a complete understanding of these calculations refer to Renard (1997). It is important to observe that unless some conservational agriculture practice is used on the land, the factor is assumed to be 1 (Ramlal and Baban, 2007).

Appendix C – Erosion 3D Parameter Description

C.1. Bulk Density

The bulk density refers to the total density of the overall mass including pore volume. The density is calculated after heating an undisturbed soil sample taken at 20 - 25 cm below the surface, at 105 °C. An error of 100 kg/m³ in the bulk density value might generate a 20 % error in the simulation due to the strong significance of this variable. When the other parameters are maintained as constants, after exceeding a minimum bulk density value, the latter and soil loss show a linear relationship. When bulk density values cannot be estimated from site samples, ranges and mean values can be based on the German Soil Erosion Research program findings on bulk density for different type of soil classes (Table C.1.). Other tables exist for bulk density estimates based on soil class, year period and type of crop.

Table C.1 - Bulk density range of	values based on soil class	(Michael et al, 2001)
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Soil class	Bulk density [kg/m³] intensively loosened - extremely compacted	
Sandy soils	1190 - 1670	
Loamy soils	1190 - 1960	
Silty soils	1190 - 1530	
Clayey soils	920 - 1320	

C.2. Initial Water Content

The initial water content is the water content (%) measured at the beginning of the rainfall event at a depth between 2 and 25 cm below the surface. A sensitivity analysis shows that after passing above the initial water content threshold value for runoff and erosion, soil loss and this parameter exhibit a linear relationship. An error of 5 % in the estimation of the initial water content value can yield an error of 25 % in the estimation of soil loss. In temperate regions, the lowest values for this parameter are found in summer due to high solar radiation and evapotranspiration rates, and the maximum values in winter. Values of initial water content can be estimated by using the ranges of values proposed by Michael et al (2001) for different soil classes (Table C.2). While it is recommended to use the maximum value of this range for short term simulations, the mean value is recommended for long term simulations.

Table C.2 - Initial water content range of values based on soil class (Michael et al, 2001)

Soil texture	Initial soil moisture content [vol. %] very dry - extremely moist
Sandy soils Silty soils	6 - 40 17 - 45
Loamy soils	28 - 50
Clayey soils	48 - 60

C.3. Organic Carbon Content

Organic matter consists of dead animal and plant mass in the soil content. The soil loss decreases as the organic carbon content in the soil increases and after reaching a maximum value, no more erosion loss is generated. An error of 0.25 % in the estimation of the initial water content value can yield an error of 19 % in the estimation of soil loss.

C.4. Critical Momentum Flux / Erosion Resistance

In order to detach a particle of soil from its surface matrix, a momentum exceeding the critical momentum must be applied. The main forces influencing this critical force are soil cohesion and gravitation. In other words, soil resistance to erosion decreases as grain size increases, while it later increases with larger

particle diameters. Thus, silty or fine sand soils have lower erosive resistance than clays or sands (Figure C.1). A summary of the relevant erosive resistance ranges for this project is found in Table C.3.



Figure C.1 - Schematic representation of the relationship between erosion resistance and particle size (Michael et al, 2001)

Table C.3 - Erosive resistance values for the textural classes available in the s	studied
watershed	

	Erosive Resistance	
KA 4 Textural Class	Assuming settling and consolidation of soil structure (conservation tillage), 10 weeks after seedbed preparation	
Ls2/Ls3/Ls4/Lts	0.001 - 0.015	
Ts3/Ts4	0.002 - 0.030	

Soil erosion has an inverse relationship with erosion resistance, so as the resistance increases, the soil loss decreases. This parameter encounters a wide variability in time and space even within the same soil class, so values from other studies should be carefully chosen. Erosion resistance values can be estimated for various types of soil class and agriculture practice or stage. As Michael et al (2001) mentions, even though a large number of experiments have been

performed in order to categorize the erosive resistance, still much data is missing. For instance, no table for different land uses from agriculture is available and for clay soils subject to any land use.

C.5. Hydraulic Roughness

The factor that takes into account the effect of surface irregularities (aggregates or superficial plants) on the velocity of surface flow is called the hydraulic roughness. This parameter is called the Manning parameter "n" in Manning's equation. The sediment transport capacity of the flow decreases as the hydraulic roughness is increased. On the other hand, the soil loss decreases exponentially with increases in hydraulic roughness. The error on soil loss calculations increases as the over/under estimation of hydraulic roughness coefficient increases and can reach 75 % if the error in the n coefficient is less than 0.005 s/m³, for n coefficients less than 0.001. Information on the hydraulic roughness coefficient *n* values for different land uses can be found in many sources such as Mays (2005) and Michael et al (2001).

C.6. Degrees of soil cover

The degree of soil cover is the percentage of land that is covered by plant residue or plants, limiting direct exposure of bare soil with the atmosphere. This coverage layer protects the soil by reducing splash erosion, absorbing part of the rain's erosive momentum, increasing infiltration and interception rate and soil capacity, and enhancing hydraulic roughness. Soil cover can vary throughout the year, depending on the weather and seasonal characteristics.

C.7. Correction factor

Due to the simplified assumptions regarding infiltration in the Erosion 3D model, a dimensionless factor is included in the input parameter. This factor is a correction for the vertical variations in the physical properties of soil, the dynamic processes that affect infiltration during rainfall, and the generation of pores caused by biological and physical processes. When the infiltration rate prediction is too low, the correction factor should be less than 1. Since all the values for this parameter included in the Parameter Catalogue of Erosion 3D deal with agricultural practices and crop characteristics that are not known for the crops in the catchment, the correcting factor had to be calibrated.



Appendix D – Event results at the Construction Site

b) 9-AUGUST AT CONSTRUCTION SITE

c) 24-AUGUST AT CONSTRUCTION SITE







e) 5- SEPTEMBER AT CONSTRUCTION SITE



f) 13-SEPTEMBER AT CONSTRUCTION SITE



g) 5-OCTOBER AT CONSTRUCTION SITE



Appendix E – Event Results at the Acono Wt Plant



b) 13-OCTOBER AT ACONO WT PLANT







e) 4-NOVEMBER AT ACONO WT PLANT



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