Evaluation of road erosion prediction models applied to unpaved roads in a small tropical watershed in Eastern Brazil

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Abstract

Tropical regions have extensive networks of unpaved roads which can be the largest contributor of sediment loading within a watershed in terms of both sediment generation and delivery. A number of erosion and sediment prediction models have been developed for unpaved roads and applied across a wide range of locations. However, little work has been devoted to the comparison of these models or to their application in tropical environments.

A 13 square kilometer mixed land use watershed in Eastern Brazil was used as a case study area for model application and comparison. Models chosen for evaluation were WEPP: Road, SEDMODL, and STJ-EROS. To determine the applicability of these models to the case study watershed, a classification system was developed to score road segments according to sediment production and delivery potential. Field observations provided data for the input parameters of the models as well as to identify which road segments appear to be high contributors of sediment within the watershed. These road segments were compared with the segments estimated by the models to have high sediment yields. The models identified less than 50% of those roads categorized by field observation as having high erosion potential. WEPP: Road matched more closely to the field observations than SEDMODL and STJ-EROS. To be useful tools for watershed management in the tropics, a unified method for calculating sediment delivery is needed as well as an adjustment to model input parameters so that they better reflect conditions in tropical watersheds.

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Chapter 1. Introduction

1.1 Background

Erosion and sedimentation are top issues in today's global society because they result in degraded soils and landscapes, pollution of surface waters, and reduced capacity of water bodies to function properly (Akay et al., 2008; Bahadur, 2009; Bruijnzeel, 2004; National Research Council, 2008; Pejon and Lyrio da Silveira, 2007; Reid and Dunne, 1984). Studies on erosion and sediment control are predominately conducted in temperate regions and these results may not always apply to tropical regions (Harden, 1992b; Ramos-Scharrón and MacDonald, 2007; Rijsdijk et al., 2007). The tropics differ from temperate regions in terms of soil type, vegetation, temperature and precipitation patterns, land use practices, as well as the type and degree of development. In addition, the primary focus in reducing sediment loads is often soil conservation on cropland with agricultural lands often identified as significant sediment sources. In less developed countries however, recent studies have shown that footpaths and unpaved roads can be a major source of sediment (Elliot et al., 1999; Ramos-Scharrón and MacDonald, 2007; Rijsdijk et al., 2007; Ziegler et al., 2004).

A functional road network is fundamental to the economic development and overall well-being of a community (Kumar and Kumar, 1999; Ziegler et al., 2004). The severe degradation of rural roads and footpaths has been noted in many countries throughout South America, Africa, and Asia (Tognetti and Johnson, 2008). Not only do the poor conditions of such roads present problems to the local community, but also to the surrounding water quality. Recent studies have shown that unpaved roads and trails can be a significant source of sediment within a watershed, although they often represent the smallest percentage of land use (Elliot et al., 1999; Ramos-Scharrón and MacDonald, 2007; Rijsdijk et al., 2007; Ziegler et al., 2004). This is particularly true in tropical regions which have extensive networks of unpaved roads with steep topography and erodible soils, and are subjected to seasons of heavy rain.

The significance of roads and trails as a sediment source has implications for how erosion is controlled and how the transportation network is managed. Without a more complete understanding of the sediment contributions from each component within a watershed, it is not possible to develop a sound remediation and management plan. Road erosion prediction models have been developed and applied for this purpose; however, these models have been applied mainly in the northwest United States. More research is needed to evaluate the suitability of these models for application in tropical watersheds.

1.2 Objectives

Sediment from unpaved roads affects both road infrastructure and environmental quality within a watershed. The first objective of this study is to evaluate the applicability of existing road erosion models for predicting sediment yield and delivery to streams in upland tropical watersheds. A set of criteria are defined for the prediction of road erosion in tropical conditions. Using these criteria, existing models are evaluated as to their potential for use in a case study application to the Corrego Horizonte watershed, a small tropical watershed in Brazil. Three candidate models are selected for further evaluation based on how close they relate to each criterion.

The second objective of this study is to evaluate the performance of the selected models in identifying critical road segments in the Corrego Horizonte in terms of sediment generation and sediment delivery to streams. In the absence of observed sediment loads from road segments, each model's performance is evaluated based on their ability to provide an accurate relative ranking of road segments in terms of severity of erosion potential. To do this, a field classification system is developed to rank and prioritize road segments with high erosion and sediment delivery potential. By comparing field rankings to model rankings of each road segment, the relative accuracy of each model can be evaluated. With regard to application in the tropics, this study identifies strengths and limitations of existing models and approaches, providing recommendations for improvements.

The overall goal of this research is to identify a model or models, suitable for use in tropical conditions, which can provide an estimate of sediment contributions from unpaved roads in a watershed. One purpose of this model is to provide land managers with a tool that can identify road segments with a high potential for erosion and environmental impact using simple field observations and/or basic measurements. By targeting roads that contribute large amounts of sediment to the water bodies within a watershed, management practices which reduce sediment loading can be more effectively identified and implemented in areas of concern.

Chapter 2. Literature review

In order to assess the environmental condition of a watershed, each source of pollution must be located and evaluated. Erosion is a particular concern in a watershed as the sediment loading from various sources can significantly pollute water bodies. Not only is it important to understand what causes sediment production at each source, but how and where that sediment is delivered throughout the watershed. The goal of this literature review is to highlight unpaved roads as a source of sediment, to identify the environmental effects of unpaved road networks, and identify the factors that contribute to road erosion and instability.

2.1 Sediment

Sediment production is a natural process that occurs from forces such as wind, rain, and snowmelt. Sediment yield can be defined as the quantity of sediment that is created from an eroding source and transported during a time interval throughout a watershed to an outlet point (Ferro and Porto, 2000). Anthropogenic forces have led to increased sediment yield, negatively affecting water quality, habitat, and infrastructure. Specifically, construction of roads and human settlements as well as conversion of undisturbed land to cultivated land generates large amounts of sediment. Such activities do not generate sediment in one single event, but rather create conditions for the continuous production of sediment over time. The natural make-up of a soil’s structure as well as the climate, topography, and surrounding vegetation, all determine the erodibility of a soil (Elliot et al., 1999a). Soil texture and particle size can influence erodibility. Luce and Black (1999) determined that high clay content soils have a lower potential for erodibility than high silt content soils and that larger particles move more slowly than smaller particles. Besides basic soil properties, rainfall intensity, slope, slope length, vegetative cover, and management practices affect soil erosion (Bahadur, 2008). It is important to understand how each factor affects the potential for erosion so appropriate management practices can be implemented to protect the landscape.

In order to manage erosion, sediment must be quantified within a watershed according to the type and number of sources and the amount of sediment produced from each. A common method of quantification is through the use of a sediment budget which identifies the amount of input, output, and storage of sediment from each source within a fixed area. Sediment is generated from all types of land surface types including unpaved roads, streambanks, hillslopes, uprooted tree rootwads, road cut-slopes, agricultural fields, forests, etc. (Ramos-Scharrón et al., 2007a; Cerda, 2007). Quantifying the contribution of sediment from each source within a watershed is a method of describing its spatial movement and storage (Nagle et al., 1999; Ramos-Scharrón et al., 2007b; Vanacker et al., 2007). These sources and sinks can be geologic features (hillslopes or streams), anthropogenic features (roads), or natural events (landslides); each is affected by land use and vegetative cover as well as by the hydrological conditions of the watershed (Vanacker et al., 2007).

The nature of sediment and its cohesive properties make it an important transportation medium for various pollutants such as chemicals, metals, and pathogens. The adsorption of bacteria and nutrients to a sediment particle is controlled by Van der Waals forces, electrostatic interactions, and hydrophobicity (Ferguson et al., 2003). When sediment enters a water body, bacteria, nutrients, and chemicals often desorb and enter the water column, thus degrading water quality. Apart from transporting pollutants, sediment negatively affects stream habitat for fish and other aquatic organisms by increasing temperature, decreasing dissolved oxygen content, obstructing migration, and interfering with specific habitat features (Akay et al., 2008; Clayton et al., 2009; Jarritt and Lawrence, 2007). Sediment decreases the carrying capacity of reservoirs and water bodies, creating problems for infrastructure and maintenance (Bhattarai and Dutta, 2008; Reid and Dunne, 1984, Elliot et al., 1999a).

2.2 Rural Roads and Trails

2.2.1 Importance to Developing Areas

Road networks are essential to any society because they provide the ability to move people, resources, and ideas from location to location. Roads that connect rural, developing communities are usually unpaved and often poorly constructed due to the lack of resources and infrastructure devoted to such remote areas. These roads however are particularly vital to rural communities because they are often the only connection to the rest of the country (Kumar and Kumar, 1999; Ziegler et al., 2004). The poor conditions of such trails and pathways present multiple problems for both the community and the watershed. Rural roads and trails in developing countries are typically made of compacted dirt which is easily detached during periods of heavy rain. Rills and gullies form over time making the road impassable and treacherous to vehicles. Any impedance will delay the time for people to move resources, thus reducing efficiency and potential profits. Unpaved roads also present problems to the surrounding environment. They can change hydrologic characteristics within a watershed, cause mass wasting, and generate surface erosion (Elliot et al., 1999). Sediment from unpaved roads is thought to be a major contributor to total sediment production within a watershed (Reid and Dunne, 1984). This sediment travels on the road surface and is ultimately delivered to waterways where it affects aquatic life and water quality.

2.2.2 Effects of Roads

Although roads are important to the transportation of people and resources as well as for security and protection, they have negative effects on the surrounding environment. The construction of roads leads to habitat fragmentation, hydrologic changes, accelerated erosion, stress on stream channel morphology, decreased biodiversity, and reduced water and air quality (Clayton et al., 2008; Lamb, 2009). Roads can negatively affect hydrology by intercepting rainfall, concentrating the flow, and thus rerouting it along paths that it may not have traveled formerly (Furniss et al., 2008). As a result, roads change the hydrologic patterns within a watershed, changing runoff pathways, peak flow volumes, runoff velocity, and stream flow hydrographs (Furniss et al., 2008). Roads can also transport chemicals and nutrients from nearby fields or from vehicles traveling over the surface (Clayton and Knoepp, 2008). Since roads are often connected to streams, these chemicals and nutrients can directly enter the water. The removal of vegetation for the creation of roads or development nearby roads can increase nutrient inputs to a nearby water body, negatively affecting water quality and organism health (Clayton and Knoepp, 2008). All of these effects can vary by spatial and temporal scales (Sheridan and Noske, 2007). One road segment can immediately affect water quality in a stream by adding sediment to the bedload; over time drinking water quality, reservoir capacity, and species diversity can be negatively affected by multiple road segments within the watershed (Sheridan and Noske, 2007).

Besides water quality, roads can negatively affect air quality; the passage of vehicles across the surface of unpaved roads can generate and emit lots of dust (Lamb, 2009). The dust particles that are transported in the air can affect visibility and human health, leading to problems such as asthma or other lung problems (Lamb, 2009).

2.2.3 Road Design

The design of a road surface has important implications for its potential for erosion. Roads can be constructed as crowned, insloping, or outsloping (Elliot et al., 1999a). Figure 2.1 illustrates each type of road shape.

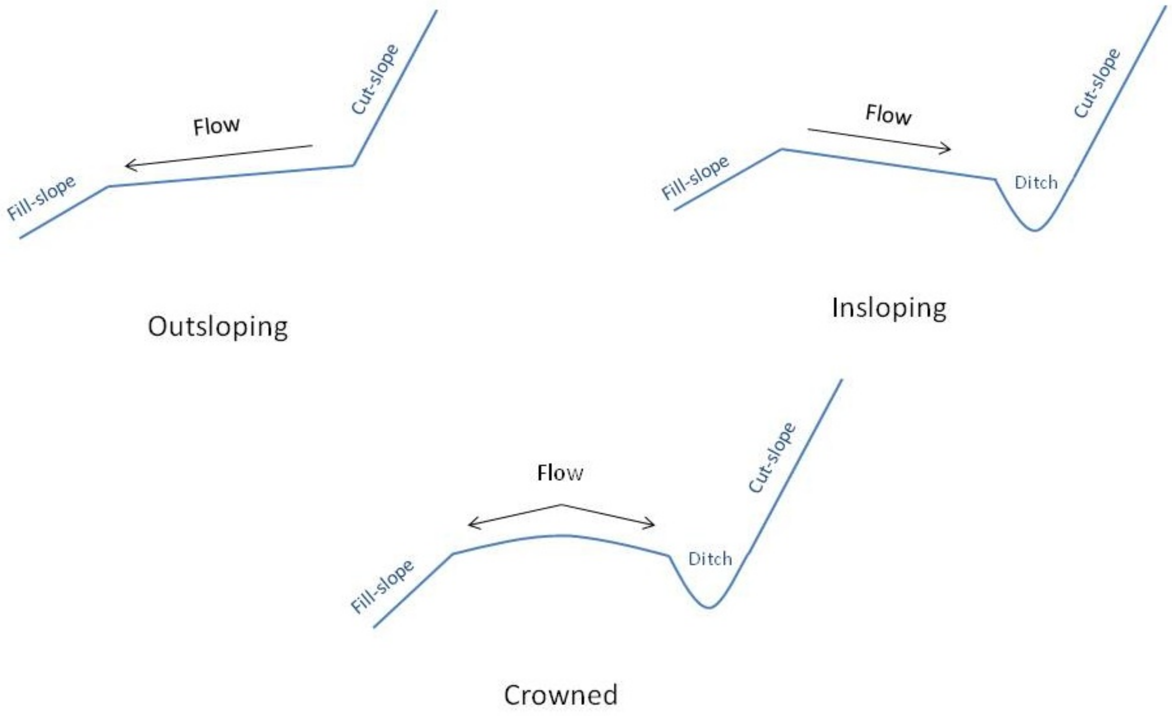

Figure 2.1. Depictions of outsloping, insloping, and crowned road surfaces.

Insloped roads are constructed with a ditch along the inside of the road to help control and direct water movement. These ditches allow engineers to plan the location of water outlets to minimize erosion (Elliot et al., 1999a). This type of road is generally more expensive to construct and is less common than outsloped roads (MRC, 2009). Outsloped roads do not have a ditch, and instead are assumed to disperse flow uniformly off the surface (Elliot et al., 1999a; MRC, 2009). To allow for drainage, rolling dips or water bars are used. Rolling dips are breaks in the slope which allow for the drainage of runoff (MRC, 2009). Water bars are constructed either of natural aggregate materials or of rubber; in either case, they are not preferred because they tend to break down with traffic (MRC, 2009). Other common drain types include: mitre drains, which are placed on roads located on ridge tops to redirect runoff; culverts which redirect runoff through concrete pipes; push-outs which drain low points by directing runoff in both directions; and cross-banks which are bars on a road surface to direct runoff to a hillslope (Takken et al., 2008). Outsloped roads are not recommended in areas that have natural springs or seeps or are subject to landslides (MRC, 2009). A road with a crowned surface will disperse flow on either side of the road, as it is a combination of both types of surfaces (MRC, 2009).

2.3 Erosion

There are a variety of erosive processes that occur on road surfaces. A study by Negishi et al. (2008) examined the various processes and their contribution to overall runoff. Hortonian overland flow (HOF) and intercepted surface flow (ISSF) are both types of runoff that can occur across a road surface. Unpaved roads are compacted with low infiltration capacity, thus increasing susceptibility to such types of surface flow. HOF is caused by excess water flowing horizontally across a surface, whereas ISSF is considered the portion of runoff from adjacent hillslopes that is intercepted by the road (Negishi et al., 2008). An understanding of the contribution of each to total runoff, and of the factors that affect each, can provide insight into suitable management practices to be applied to specific areas. Since unpaved roads act like channels during periods of rainfall, HOF is the primary type of runoff and cause of sediment transport across a road (Jarritt and Lawrence, 2007; Negishi et al., 2008). Negishi et al. (2008) found that ISSF began after peak intensity rainfall and was typically concentrated along the side of the road. Rainfall splash may also contribute to erosion on road surfaces by through the detachment of surface particles from the intensity of rainfall (Jarritt and Lawrence, 2007). Depending on rainfall intensity, rainfall splash can increase the store of sediment available for transport on a road surface, and can thus have a significant impact overall depending on location (Jarritt and Lawrence, 2007). Rill and gully erosion are very common problems with unpaved roads and trails. Unpaved roads are not well protected by vegetation or durable surface material, thus during times of intense runoff, flow is channeled across this surface, creating both rills and gullies (Harden, 1992). The intensity of vehicular traffic can also create surface ruts.

Ziegler et al. (2002) identified a specific process of erodibility of roads during storm events. The term “dynamic erodibility” is used to describe the initial peak of sediment output which is followed by a rapid decrease in output as the sediment volume diminishes; this is followed by a gradual decrease as erodibility of the surfaces stabilizes. In this conceptualization, pre-existing loose sediment is a key factor in determining erosion and sediment production (Croke, 2006; Ziegler et al., 2002). The characteristics of this top layer will vary according to the location of the road as well as the type and amount of surface cover. Ziegler et al. (2001, 2002) argue that to truly understand the process of erosion and accurately quantify sediment production, the initial erodibility must be understood as well as the final flush of sediment after the storm. Jarritt and Lawrence (2007) similarly state that the amount of erosion depends on the material available to be transported as well as the capacity or energy of the overland flow to move the material.

Erosion from road surfaces varies according to location and conditions. Luce and Black (1999) collected a large range of sediment samples from their site in Oregon. Most roads did not produce high yields of sediment, but rather a few road segments contributed the majority of sediment (Luce and Black, 1999). This implies that by focusing on the road segments with high erodibility, overall sediment production can be decreased significantly.

2.3.1 Factors generating erosion

The type and amount of traffic on a road affects erosion and sediment production (Elliot et al., 1999a; Ziegler et al., 2004; Ramos-Scharrón et al. 2007a). Reid and Dunne (1984) state that traffic is one of the most important factors affecting road erosion. Roads that have regular traffic by heavy vehicles typically generate more sediment than trails used by animals and people. Sheridan and Noske (2007) summarized their results of traffic studies indicating that traffic can increase sediment production two to twelve times that of base conditions. In study conducted in Thailand, rural roads and trails with traffic produced, double that of un-trafficked roads (Rijsdijk et al., 2007). Additionally, the construction and maintenance of the road can increase the erosion rate of a road network (Elliot et al., 1999). Construction and maintenance of unpaved roads typically involves the addition of natural material to reconstruct the road bed or stabilize ruts and gullies; the amount of sediment available for transport can be increased significantly.

More specifically related to the characteristics of each road segment, Luce and Black (1999) theorize that road length, slope, cut-slope height, soil texture, and maintenance affect erosion. Road length and slope are primary factors affecting sediment production and delivery (Ebisemiju, 1990). The length and slope of a road segment affect the shear stress and power of surface flow, which thus affects the rate of erosion of surface material. Sheridan and Noske (2007) found that slope affects sediment production up to three times greater when intense overland flow runoff occurs as opposed to processes such as interrill or splash erosion. Road segments with steep slopes tend to have greater values for critical shear stress so transport capacity is greater (Luce and Black, 1999). Based on empirical equations set forth by Luce and Black (1999), it is evident that erosion is proportional to length and slope. They found that increasing the length on roads with steep slopes leads to increased sediment production.

While road length and slope are primary factors indicating erosion, cut-slope height, soil characteristics, and road maintenance can increase or decrease the amount of sediment available for transport. Cut-slope height can also affect sediment production based on its relationship to the road. The cut-slope contributes loose material to the ditch or road surface through overland flow and slumping (Luce and Black, 1999). Unstable cut-slopes increase the amount of loose sediment available for transport along a road surface. Soil texture directly affects erosion because it is a key factor in determining how easily sediment particles can be detached from the surface. Soils with high clay or sand content are not as easily detachable as those high in silt, or fine particles. Ditches can act as a source or sink for sediment; therefore maintenance of ditches is important in decreasing erosion. If the vegetation in the ditch is left in place, sediment transport decreases. If road maintenance includes the removal of vegetation from ditches or grading of the road surface, sediment production will increase (Luce and

Black, 1999). Removal of vegetation was found to increase sediment production by a factor of approximately 7.4 when compared with no road treatment (Luce and Black, 1999).

Road characteristics can also have an effect on erosion. Infiltration capacity and the degree of compaction of the road surface can affect how quickly and how much runoff occurs. Unpaved roads are typically very compacted and have very low infiltration capacities. When heavy rain occurs, it takes a minimum amount of time before runoff occurs. In a study in Ecuador, Vanacker et al. (2007) found that the minimum rainfall intensity needed to generate runoff was considerably lower for unpaved trails than for pasture or cropland. Hortonian overland flow is more easily generated on unpaved roads than on agricultural land because of the high compaction and low soil porosity of the road surface cover (Ziegler et al. 2004; Harden, 1992b; Vanacker et al., 2007). The infiltration rate of a surface affects the transport of runoff because high infiltration rates can decrease volume and velocity of the flow (Ebisemiju, 1990). Stewart and Cameron (1992) studied the effect of trampling on soil compaction and found that water content of the soil was one of the most important factors in predicting soil compaction. In studying various soils, they determined that organic soils were unaffected by trampling and thus were not compacted; however, they should not be used for roads or trails because they have low strength and are susceptible to erosion.

2.3.2 Connectivity of runoff and sediment

An understanding of the connection between the water and sediment sources within a watershed is foundational to a correct interpretation of the causes and effects of runoff and erosion. Hydrological and sediment connectivity simply define pathways of water and sediment through sources and sinks within a watershed (Bracken and Croke, 2007). Bracken and Croke (2007) describe five major components of connectivity within a watershed: climate, hillslope runoff, landscape position, delivery pathway, and buffers. Climatic factors such as antecedent moisture, rainfall patterns, rainfall intensity and depth, and temperature can be used to identify the degree of hydrological connectivity between areas; for example, semi-arid regions are not as connected as tropical regions because base flow and storage of water are not as deep (Bracken and Croke, 2007).

Hillslopes represent a main landform and are therefore significant when considering runoff contributions. Hillslope runoff potential is determined by infiltration, surface roughness, antecedent moisture conditions, vegetation, land management, as well as the temporal variability of storm events (Bracken and Croke, 2007). All of these conditions affect the type and amount of runoff, and therefore the degree of connectivity between landforms. Landscape position is therefore important because factors such as slope length, distance, and location affect how and where runoff travels. The delivery pathway represents the method of travel for runoff across a watershed. Runoff can be concentrated in incisional flowpaths such as rills and gullies or by dispersed pathways (Bracken and Croke, 2007). Incisional flowpaths typically carry runoff of high energy potential and connect directly to outlet sources, whereas dispersed flow is shallow, wide flow which is difficult to quantify (Bracken and Croke, 2007). Finally, buffering describes the connectivity of a channel and its adjacent floodplain. The importance of a buffer is related to the degree to which it can slow down and reduce runoff and sediment delivery based on soil type, slope, and vegetation (Bracken and Croke, 2007).

Since unpaved roads provide a direct pathway for water and sediment, the location of the network is important. Depending on the topography, flow can be concentrated on the road itself or be directed to surrounding hillslopes. In mountainous environments, road networks are particularly dense and although they represent a small portion of surface area, they can have significant effects on hydrology. Road impact has been mainly predicted by estimating road density—the higher the density, the greater the impact (Takken et al., 2008). Harden (1992b) claims that when path densities are high, the dispersal of flow from roads to surrounding land areas contributes more to erosion than runoff from agricultural fields. Vanacker et al. (2007) also found that unpaved road networks provided surfaces conducive to runoff generation and the density of roads and trails was positively correlated with the amount of suspended sediment at the outlet of the watershed. In addition, Clayton et al. (2009) summarized their findings on the effects of road density on aquatic habitat, finding that increased road densities correlated with decreases in fish populations and spawning. Since roads contribute to water pollution, it is important to understand where sediment is transported and the effect on the overall health of the watershed. Recent studies also point out that the connection of roads and water quality is dependent upon delivery pathway characteristics and general hydrological connectivity (Bracken and Croke, 2007; Croke, 2006; Hairsine et al., 2002; Lane et al., 2006; Takken et al., 2008). The connection of roads to water quality has not been as heavily studied as compared to erosive processes of road segments (Takken et al., 2008). Roads can significantly affect water quality because they contribute sediment and pollutants to streams, often directly (Hairsine et al., 2002; Ziegler et al. 2004).

2.3.3 Sediment delivery

An important factor affecting the understanding of sediment transportation is the concept of sediment delivery. One way to quantify sediment delivery is through a sediment delivery ratio. A sediment delivery ratio is the ratio of sediment yield delivered at the outlet of a watershed to the sediment production the entire watershed (Walling, 1983). It compares the amount generated in a particular location to the amount that reaches the watershed outlet. The sediment delivery ratio for a given area is dependent upon climate, topography, land use, soil, vegetation, and hydrological patterns (Lu et al., 2006); more specifically, the sediment source, strength of flow, and characteristics of the delivery pathway influence how much sediment is transported to a water body (Hairsine et al., 2002). Many equations have been developed which attempt to calculate the delivery ratio based on watershed characteristics, runoff, land use, and traffic intensity, but due to the complexity of sediment and erosion processes, no one method has been adopted (Walling, 1983, Sheridan and Noske, 2007). One of the major concerns regarding sediment delivery ratios is the problem of using a single number to represent an entire watershed over a long period of time. Sediment delivery can vary according to storm event and landscape position. Ferro and Porto (2000) found that sediment delivery ratios usually decrease with increasing watershed area since slope decreases and there are more locations for storage. The use of GIS can help with this issue by assigning delivery ratios to each grid cell within a watershed so that transport can be more effectively predicted; however, the process of calculating this delivery ratio is vague and only provides estimation.

Lane et al. (2006) identified five possible delivery pathways for runoff from roads: direct infiltration into the soil by a drainage outlet; infiltration through a gully downslope;

access to the stream channel by a stream crossing; access to a stream channel through a gully; and access to a stream channel by overland flow from a drainage outlet. In a related study, Takken et al. (2008) described three types of delivery pathways: stream crossings, gully pathways, and diffuse pathways. The delivery of sediment from sources to sinks depends on features such as fill slopes, floodplains, benches, or fans located along flow paths (Wison et al., 2001). Megahan and Ketcheson (1996) also identified the presence of obstructions and drainage structures as affecting sediment delivery. As might be expected, obstructions such as downed vegetation, logs and branches, the depth of litter on cut and fill slopes, etc. reduce the amount of sediment transported. Culverts allow large volumes of sediment to be transported long distances. Conversely, rock drains are more fitted to road topography and slow down runoff and sediment. Megahan and Ketcheson (1996) found through a sensitivity analysis that sediment volume had the greatest effect on the travel distance of sediment. Source area and the slope of the hillside also were important factors in overall sediment delivery (Megahan and Ketcheson, 1996).

Sediment delivery also heavily depends on the vegetative cover of the surface. Ebisemiju (1990) found that approximately 88% of sediment was detached and transported from bare hillslopes to a stream, whereas only 16% of sediment was transported to a stream on vegetated hillslopes. Vegetation not only serves as a sink for sediment, it also reduces runoff volume and speed, and protects the ground from the effect of rainfall splash. The leaves and stems of plants provide resistance against runoff, decreasing the energy of the flow, and allowing sediment to deposit on the slope (Ebisemiju, 1990). The characteristics of the soil will also affect sediment delivery ratio, especially travel time. Lu et al. (2006) found that the sediment delivery ratio decreases as particle size increases and soil texture changes from clay to sand.

2.4 Road management recommendations

Road maintenance or management techniques can be used to help reduce erosion and sediment production from unpaved roads. These suggestions vary according to location, road characteristics, as well as cultural, political, or economic constraints. Most suggestions relate to road construction. The main objective is to remove the flow of water from the road surface. This can be done through the construction of ditches and/or drainage points. Negishi et al. (2008) recommends the installation of ditches along the cut-slope as a way to move water off the road and thus decrease the time that the road is wet and saturated. Similarly, the work of Takken et al. (2008) suggests drain spacing as a key management practice for unpaved roads. Since drains directly affect hydrology, the density and type of drains are important to consider. If the volume of runoff from the road is known, drain location and type can be adjusted to handle the type of flow. Ziegler et al. (2004) suggests techniques such as limiting road length, reducing road gradient, improving road repair methods, or by reducing the ability of the road to transport sediment. Since traffic intensity directly affects sediment production, Elliot et al. (1999a) suggests reduced tire pressure for vehicles traveling on unpaved roads because it has been proven to reduce rut formation and thus decrease erosion. Adding gravel or some type of aggregate has also been shown to reduce erosion and sediment production from unpaved roads. Studies conducted in the northwestern United States and Texas have shown that gravel has increased hydraulic conductivity decreased erosion by more than 80% and 35%, respectively (Elliot et al. 1999a).

Road removal or replacement is a costly option that is often the last alternative (Takken et al., 2008). Models can be used to simulate the effect of removing a road on the volume of runoff within the watershed. Replacement or maintenance can be performed on those roads identified as having the highest potential for erosion. Furniss et al. (2008) suggests land managers and engineers identify roads with a high potential for erosion and sediment delivery, consider their location within the landscape, and add drainage structures which would divert runoff to areas with increased infiltration capacities.

2.5 Erosion prediction models

Models can be physics-based or empirically-based. Physics-based road models calculate erosion of a specific road segment based on the predicted hydrologic behavior of a road surface (Fu et al., 2010). As a result, physics-based models are useful for analyzing the impact a road may have on a water body. They are applicable in a variety of environments because they are based on the physics of erosion, which are the same everywhere. Physics-based models require extensive calibration, and they require accurate data which is often hard to estimate or measure (Fu et al., 2010). Empirical road models use relationships between the factors that affect sediment production (Fu et al., 2010). Empirical models can predict loading across an entire watershed with the ability to identify specific areas of high erosion potential (Fu et al., 2010). They utilize factors which are easier to estimate, however the factors vary according to the environment, so empirical models are more difficult to apply in locations other than the origin of development. In addition, the assumptions made in calculating sediment production within a watershed simplify the model and can reduce accuracy (Fu et al., 2010).

Current models that have been developed to simulate road erosion do so at various temporal and spatial scales. Some models simulate erosion on one road segment and heavily focus on various erosive processes, whereas other models focus on the watershed scale and simulate erosion across a road network. For watershed assessment purposes, the intent of understanding erosion and sediment production is to prioritize areas for remediation and protection. Thus, it is important that models are able to simulate erosion on a watershed scale. The use of Geographic Information Systems (GIS) has enabled researchers to represent a watershed as a series of cells, to which specific parameters can be assigned (Harden, 1992b). Parameters such as soil type, land use, slope, infiltration rate, etc, allow landscape areas to be identified, hydrology defined, and erosion rates calculated. Many models incorporate GIS as a way to model erosion on a watershed scale more efficiently. The following section briefly describes several available erosion and delivery prediction models.

2.5.1 SEDMODL

The Boise Cascade Corporation and National Council on Air and Stream Improvement developed SEDMODL to predict sediment yield from roads to streams in a forested watershed (NCASI, 2005). The model identifies four locations that produce sediment: road surface, cut-slope, fill-slope, and ditch. Based on observations, revegetated fill-slopes were ignored due to the negligible production of sediment; sediment from the road surface and ditch was combined into tread sediment. The total sediment delivered from a road segment is therefore based on the road tread (both running surface width and ditch width) and cut-slope. Sediment from the road tread is based on road length, width, and slope, geologic erosion rate, road surface type, traffic intensity, precipitation, and sediment delivery. Sediment from the cut-slope is based on cut-slope vegetation, slope, geologic erosion rate, road length, and sediment delivery. The sum of sediment from the road tread and cut-slope is then multiplied by a road age factor. This factor designates whether the road segment was created or graded within the last year.

All factors are based on field studies and observations from forest road studies in Washington, Oregon, Idaho, North Carolina, and Virginia (NCASI, 2005). The values for geologic erosion rate, surface condition, traffic intensity, road gradient, precipitation, sediment delivery, and cut-slope height and vegetation are assigned a relative factor value according to tables in the user manual, also provided by the work of Akay et al. (2008). A revised version of SEDMODL, called SEDMODL2 was developed with Microsoft Access and GIS (NCASI, 2005). SEDMODL2 utilizes the same equations and basic input parameters. The geologic erosion rate is defined based on the erodibility of the soil in terms of its lithology and geomorphic age (NCASI, 2005). The delivery factor associated with each segment is estimated by looking at the distance between the middle of the road segment and that of the nearest stream. SEDMODL assumes that if a road crosses a stream, the delivery factor is 100%; if a segment is within 30 to 60 m of a stream, the delivery factor is between 35 and 10% (Akay et al., 2008). Cut-slope cover factor is the percentage of non-erodible cover on the road, cut-slope, and fill-slope areas. The cut-slope height is based on the slope of the hillslope.

The model can be implemented with GIS; the roads that have the highest delivery factor can be highlighted as areas that would benefit from erosion control practices. The researchers noted a few weaknesses of the model based on assumptions made in the equations. The model assumes that all the roads have ditches and are in-sloped; this could over- or under-estimate sediment yield (NCASI, 2005). In addition, the model is only as accurate as the data used, which in many developing areas may not be complete. Akay et al. (2008) identified the following factors to heavily influence sediment yield: road use, gradient, and cut-slope height. Ultimately, the accuracy of the results of this study must be validated with actual field data.

2.5.2 ROADMOD

Anderson and MacDonald (1998) developed a model to estimate annual sediment production from a road network on the St. John, U.S. Virgin Islands. The model is a combination of empirical relationships developed from field data as well as a series of algorithms to utilize pertinent GIS data layers. The road characteristics deemed most important in this study included road drainage area, road gradient, surface material, road use, and road age (Anderson and MacDonald, 1998).

The road networks were mapped in the field on topographic maps, but a GIS data layer could be incorporated into the model if available. The roads were divided into segments for which length, width, and gradient were measured; drainage points or culverts were identified and marked on the map or data layer. Road surface was determined to be either paved or unpaved, and road use was chosen as low, medium, or high based on how many households were located along the road. Road age was determined as the amount of time since the last grading of the road surface occurred; this information was gathered by permit signs and local residents. The creators assume 100% of the sediment generated by the roads and directed to ditches and culverts will reach the stream. If runoff is directed to a vegetated hillslope, sediment delivery is considered negligible. If no information was provided, a ratio of 0.5 was assumed for the road segment (Anderson and MacDonald, 1998).

Using stepwise regression, Anderson and MacDonald (1998) found that road gradient, age, and drainage area best related to the erosion rate. The equation developed to relate these variables is as follows:

$$E = 0.0057AS + 0.0034m^3m^{-1}a^{-1}, \tag{2.4}$$

where E is the erosion rate in cubic meters of material removed per meter of road length per year, A is the upslope drainage area in m^2, and S is the road gradient in m/m.

This equation can be used on individual road segments, but for a network of roads and trails with varying characteristics, Anderson and MacDonald (1998) developed a program in C which uses GIS to produce a data layer with estimated annual sediment production from each road segment. The following attributes are assigned to each road segment: road length, average width, average gradient, destination point, road type (paved/unpaved/drainage point), and runoff factor (estimation of proportion of flow from hillslope onto the road segment). The model estimates sediment production for each road segment based on the proportion of runoff from the hillslopes and road segments above that point. The sediment delivered to each identified outlet is summed to produce the final sediment yield within the watershed. An assumption made by the model is that all segments transport flow to another road segment or to a segment which discharges directly to a hillslope or stream channel (Anderson and MacDonald, 1998). The erosion of each segment depends on the surface area and runoff from previously connected road segments.

Six assumptions are made in ROADMOD: 1) the majority of road runoff is conveyed by the road surface; 2) sediment storage within a road segment is negligible; 3) ditch and cut-slope erosion is negligible; 4) average road slopes and widths are approximated for the entire road segment; 5) drainage area and sediment routing is approximated with one flow routing factor; 6) climate conditions during the study period were similar to conditions in 1990-1993 (Anderson and MacDonald 1998).

The researchers applied ROADMOD to two different watersheds on St. John and compared erosion rate estimates to sediment and turbidity measurements taken in both areas. Additional verification and validation is needed for this model. The authors of ROADMOD recognize that validation with field data is necessary and that the assumptions made in the model may not be applicable in other watersheds. Improvements that can be made to the model include the incorporation of a time-dependent erosion variable and estimations of erosion for cut-slopes, fill-slopes, and drainage ditches. In addition, the model should be calibrated to individual runoff events so various weather conditions can be modeled (Anderson and MacDonald, 1998).

2.5.3 STJ-EROS

The St. John Erosion Model (STJ-EROS), developed by Ramos-Scharrón and MacDonald (2007b) is a program based on ROADMOD and integrated with GIS to predict sediment production from multiple sources within a watershed. The specific objectives for the study involving the model were to 1) develop a sediment budget for St. John; 2) use the model to quantify sediment production from unpaved roads and trails; and 3) compare the predicted sediment yields with field data (Ramos-Scharrón and MacDonald 2007b).

The model predicts sediment production by dividing a watershed into landscape units and assigning user-defined sediment delivery ratios (SDRs) to each unit; the following landscape units are used in STJ-EROS: streambanks, treethrow, undisturbed hillslopes and zero-order catchments, roadways, and road cut-slopes (Ramos-Scharrón and MacDonald, 2007b). STJ-EROS has six input routines and five calculation routines (figure 2.5). The equations utilize variables input by the user and pre-set values based on runoff rates and sediment field measurements taken by Ramos-Scharrón and MacDonald (2007a, 2007b) in St. John for each landscape unit using methods appropriate for each defined area. The six user inputs include sediment delivery ratios, the watershed area, the annual rainfall rate, the number of years for which the model is to be applied, and the names of the GIS data layers that will display the results. The model then calculates sediment production and delivery rates for roads, streambanks and treethrow, and undisturbed areas. The final product is two data layers, one presenting sediment production from roads and one presenting sediment production from natural sources.

A specific routine in STJ-EROS is used to calculate sediment yields from the road network within the watershed. It requires four input layers and four user-defined variables. The first layer is a line layer that lays out the road segments and characterizes each segment with road surface type, grading frequency, slope, length, and width. The second layer contains the coordinates for the drainage point of each road segment. Sediment production is then calculated based on the user inputs for SDRs, annual rainfall, and road characteristics; paved roads are assumed to contribute no sediment to the watershed. The researchers claim that STJ-EROS calculates road sedimentation more accurately than ROADMOD because the equations used in estimation are based on more accurate field measurements (Ramos-Scharrón and

MacDonald 2007a, 2007b). The model includes assumptions based on specific site characteristics and assumes runoff occurs after 6 cm of rainfall. Such assumptions create a challenge to broader use of the model, and application of STJ-EROS to other locations was not found in the literature.

STJ-EROS was applied by Ramos-Scharrón and MacDonald (2007b) to three different watersheds on St. John. The model predicted that unpaved roads yielded the greatest amount of sediment to the watershed and identified which roads had a high potential for erosion. Compared to other field data and models, STJ-EROS appears to underestimate sediment yields; however, the predicted sediment yield values were comparable to measured values, providing basic validation for the model (Ramos-Scharrón and MacDonald 2007b).

2.5.4 WARSEM

WARSEM is an empirical model developed by the Washington State Department of Natural Resources to predict sediment delivery from roads to streams (Dubé et al., 2004). This model was developed from SEDMODL and utilizes the same three equations to calculate sediment production and the same factors as SEDMODL and SEDMODL2 (Dubé et al., 2004). Data from SEDMODL2 can be run using the WARSEM interface. The benefits of WARSEM, as outlined by Fu et al. (2008) include the following: it can be applied at catchment scales; it incorporates the major factors involved in road erosion; it is useful for management purposes; it can be implemented with GIS; it can be modified to different settings; and the data required for input is easily collectable. The user inputs include average rainfall, road surface material, vegetation cover, slope, traffic and maintenance factors, and drainage area. WARSEM has four application levels according to the data available to the user and the level of output desired. It can be used to simply estimate road erosion from a few segments or be used to simulate the effect of best management practices within a watershed. There are five options for sediment delivery; based on the distance of the road to the stream, the road is assigned a factor of 0 to 5 (Dubé et al., 2004). This may limit the accuracy of the calculated sediment production and sediment delivery ratio since the effect of vegetation or other surface characteristics cannot be specified as inputs to the model. The model is free online, but it’s applicability to tropical environments is somewhat limited because it was initially developed for the state of Washington, and the user has a limited selection of locations to use for background climatic and stream data.

The model was validated by comparing monitoring data taken from the watershed to that of the model results. The erosion rates predicted by WARSEM were also compared to erosion rates computed for a nearby forest road network. Fu et al. (2008) used the model in a study in Australia and determined that the model has the propensity to overestimate erosion rates and sediment delivery, probably because of the high sensitivity of the traffic and road surface factors.

2.5.5 KINEROS2

In order to simulate the transport of loose surface material from an individual road segment throughout a storm event, Ziegler et al. (2001) developed a model, KINEROS2 based on KINEROS (The Kinematic Runoff and Erosion Model) which predicts runoff and sediment production on unpaved mountain roads; it does not take into account the addition of sediment from surrounding features (Fu et al., 2010). This model was validated using data from simulated rainfall events and was found to accurately simulate discharge and sediment output (Ziegler et al. 2002). The process of sediment output during a storm event is described by Ziegler et al. (2001) as the following: an initial peak of sediment output followed by a rapid decrease in output as the sediment volume diminishes, with a gradual decrease as erodibility of the surfaces stabilizes. The amount transported is dependent upon the ability of the surface flow to remove the loose layer of material on the road surface, as well as to detach compacted material from the surface (Ziegler et al. 2001). As mentioned earlier, this phenomenon is described by the researchers as “dynamic erodibility.” These multiple states of erodibility have implications for how sediment output from roads is modeled. KINEROS2 is a physics-based model which models the discharge and output of multiple-sized sediment particles for specific events (Fu et al., 2010).

A series of equations are presented in the work of Ziegler et al. (2001; 2002) which relate the following factors: rainfall intensity, fraction of covered soil, depth of surface runoff, susceptibility of surface to rain splash detachment, settling velocity of sediment, and pre-storm sediment availability. Ziegler et al. (2002) improved the

KINEROS2 model with an exponential decay equation specifically designed to portray Horton overland flow, splash erosion, and infiltration. KINEROS2 outputs runoff characteristics, sediment output, and sediment concentration for a rainfall event (Fu et al., 2010). Sediment transport is modeled indirectly by incorporating a mass balance equation for sediment transport based on local concentration, erosion and deposition rates, and water flow rate (Ziegler et al., 2001). Sediment delivery is not considered since the spatial scale is restricted to one road segment. Extensive calibration and validation of KINEROS2 is detailed in the work of Ziegler et al. (2001). The authors noted that the model still does not estimate peak sediment outputs as accurately as hoped and that more calibration is needed in this area. In addition, the study done by Ziegler et al. (2002) does not assess the capability of KINEROS2 to model sediment delivery from roads to streams. Fu et al. (2010) suggests the usefulness of KINEROS2 for research applications rather than land management. The model provides a good representation of source erosion from a road segment, however data inputs are extensive and the model is complex to use.

2.5.6 WEPP

The Water Erosion Prediction Project (WEPP) is a physics-based model that has been adapted to predict erosion from a variety of land uses including roads, forests, and agricultural fields (Flanagan et al., 1995). WEPP: Road is the version adapted to simulate erosion from an individual segment; WEPP: Road Batch predicts erosion for a network of roads throughout a watershed (Elliot et al., 1999c). These versions have been developed for both Windows and the internet, making it easy for those who have no previous experience with the model. For WEPP: Road, the user inputs data for climate, topography, soil texture, and years to run the model (Elliot et al., 1999c; Tysdal et al., 1999; USDA, 2009). The climatic data includes information about maximum and minimum temperature, average rainfall depth, and number of wet days (USDA, 2009). WEPP and therefore WEPP: Road, generates a series of precipitation events and calculates the amount of rainfall excess by comparing rainfall rates to infiltration rates and storage rates; runoff is identified as the amount of rainfall excess and is calculated before routing across the defined surfaces (Stone et al., 1995). Horton overland flow is the only erosive process considered (Stone et al., 1995). If runoff occurs, WEPP uses a series of algorithms to determine erosion rates and sediment delivery (Elliot et al., 2009; Flanagan et al., 1995). The user inputs road characteristics including road surface, traffic level, road gradient, road dimensions, fill-slope and length, buffer slope and length, road cover type, and road design (Elliot et al., 1999c; USDA, 2009). The model defines three overland flow elements (OFEs): road surface, fill-slope, and buffer (USDA, 2009; Elliot et al., 1999c). WEPP: Road outputs the annual runoff depth (mm) and the average annual amount sediment leaving the road and the buffer (kg) (Elliot et al., 1999c; USDA, 2009). Sediment delivery is calculated by the model based on the fill-slope and buffer conditions input by the user (USDA, 2009). The model is designed to run approximately 30 years of climate data, however outputs can be obtained for specific events or years (USDA, 2009).

WEPP: Road is limited in that the data requirements, specifically related to climate, can be difficult to obtain. The model assumes that roads are free of vegetation, that fill-slopes have 50% vegetative cover, and the buffer is representative of a 20-yr old forest (Elliot et al., 1999c). In addition, the model does not take into account all characteristics of the road surface such as ephemeral gullies, channels, or landslides (Brooks et al., 2006). Brooks et al. (2006) does however suggest that WEPP is a key model for watershed assessment because it can be adapted to a range of climates, soils, and topographies, and with GIS can be used for varying factors. Rhee et al. (2004) used WEPP in a study in Idaho to investigate how the level of detail of the input data affected road erosion. They determined that there was not much difference in the methods of analysis, but rather in the output of sediment delivered to the stream; lower detail methods tended to underestimate sediment yield, but high detail methods underestimated sediment *delivery*. In addition, a sensitivity analysis revealed that the model is not very sensitive to road characteristics, whereas it is sensitive to the methods used to describe the topography of the buffer between the road and stream. In a sensitivity analysis of WEPP: Road for insloping roads completed by Tysdal et al. (1999), it was found that road length, slope, and soil type were factors affecting erosion. The contribution of sediment from the cut-slope and ditch depends on the soil type and management practices (Tysdal et al., 1999).

2.5.7 SEDD

The Sediment Delivery Distributed (SEDD) model is primarily a sediment prediction model which focuses heavily on sediment delivery (Ferro and Porto, 2000). Sediment production is calculated based on the USLE equation and sediment delivery ratios (SDRs) calculated for each landscape unit within a watershed. The SDRs are based on travel time of sediment particles along a flow pathway from the source to the nearest stream channel (Ferro and Porto, 2000). Sediment delivery is only considered for land features, not for transport of sediment along a channel; the SDR is calculated using the following equation:

$$SDR_i = \exp\left(-\beta t_{p,i}\right) , \tag{2.5}$$

where β is a coefficient which represents roughness and runoff along the flow pathway; $t_{p,i}$ represents the travel time which is based on length of the pathway and flow velocity, calculated by the following equation:

$$t_i = \sum_{j=1}^{N_p} \frac{l_i}{v_i} , \tag{2.6}$$

where l represents the length, and v represents the flow velocity for the cell (m/s) (Fernandez et al., 2003). The flow velocity of a cell inherently takes into account the surface roughness, presence of vegetation, and changes in topography (Fernandez et al., 2003). Velocity (v_i) is thus calculated by the following equation:

$$v_i = d_i s_i^{1/2} , \tag{2.7}$$

where s_i is the slope of the cell (m/m) and d_i is a coefficient representing surface roughness characteristics (m/s), of which values are provided in the work of Fernandez et al. (2003).

In all instances where the SEDD model has been used, the coefficient, β, must be estimated. Fernandez et al. (2003) used an inverse modeling approach in which known values of SDR are used with factors such as drainage density, soil type, area, and slope. The following equation utilizes this approach to estimate β:

$$SDR_w = \frac{\sum_{i=1}^{N} \exp\left(-\beta t_i\right) l_i^{0.5} s_i^2 a_i}{\sum_{i=1}^{N} l_i^{0.5} s_i^2 a_i} \quad , \tag{2.8}$$

where SDR_w represents a known sediment delivery ratio, N is the total number of cells in the watershed utilizing GIS, l_i is the length of the flow path, s_i is the slope of the cell, and a_i is the area of the cell (Fernandez et al., 2003).

In order to calculate the final sediment yield for the watershed, the SEDD model uses the following equation incorporating the SDR, soil loss, A (t/ha) and area, SU (ha) (Ferro and Porto, 2000):

$$Y_i = SDR_i A_i SU_i. \tag{2.9}$$

The method of calculating soil loss is up to the user. Ferro and Porto (2000) used the USLE equation,

$$A_i = EF_i K_i L_i S_i C_i P_i \ , \tag{2.10}$$

where EF_i is the erosivity factor, K_i is the soil erodibility factor, L_i and S_i are the topographic factor representing slope and slope length, and C_i and P_i are cover and management factors.

A study in Thailand completed by Bhattarai and Dutta (2008) compared the SEDD model which utilized the RUSLE equation, with MUSLE, a physically based model which calculates sediment yields for a single storm event, and with a process based model consisting of a kinematic wave equation and continuity equation. The researchers found that the SEDD model using the RUSLE equation, over-estimated sediment production (Bhattari and Dutta, 2008). Two DEMS at 90-m and 30-m resolutions were used and it was discovered that the change in resolution greatly affected the L and S factors of the RUSLE equation, which affects sediment production. It was hypothesized that sediment yield estimations could be improved if the coefficient, β, in calculating SDR, had been calibrated using measured field values; the researchers had used a value of 1 for this coefficient because a sensitivity analysis of this factor indicated that it did not significantly affect the SDR value (Bhattari and Dutta, 2008). The process based model closely estimated the sediment yield for the watershed, based on field data, and MUSLE under and over-estimated sediment production based on the month. Bhattari and Dutta (2008) did indicate however, that the empirical models may have estimated sediment production more accurately if calibration for each model had been performed before use.

2.5.8 HEM

The hillslope erosion model (HEM) is an erosion and sediment prediction model for hillslopes and was developed by the USDA-ARS Southwest Research Watershed Center (Cogle et al., 2003; Wilson et al., 2001). This model is coupled with GIS to simulate sediment production along a flow pathway. The amount of sediment transported or stored depends on the following factors: topography, soil erodibility, vegetative canopy cover, and surface ground cover (Wilson et al., 2001). HEM is able to represent rill and interrill erosion as well as the sediment transport processes through kinematic wave equations for runoff and a sediment continuity equation (Cogle et al., 2003). Total sediment yield from the watershed to the stream network is calculated as an area-weighted sum of sediment yields from each flow pathway. The sediment yield can also be expressed as a rate so that sediment delivery can be calculated. The model does not account for roads however, and therefore may not be applicable to determine sediment delivery from roads. There has been application of HEM outside of the United States. Cogle et al. (2003) applied HEM to watersheds in India, New Zealand, and Australia and found that the model required an adjustment for the different soil properties present in each watershed. HEM is a useful model because it is available online, however Cogle et al. (2003) suggests it would be better used as an educational tool in areas outside the United States until it has been revised to account for differences in other regions.

2.6 Field measurements and methods

Although models are useful tools to predict erosion and sediment from unpaved roads, first hand field observations are essential to understanding erosive processes before, during, and after rainfall. Current erosion prediction models are limited by the lack of capability and accuracy to simulate sediment delivery. The main reason for this deficiency is the difficulty of measuring and quantifying road to stream connectivity and the subsequent sediment delivery. Despite this obstacle, simple field observations can provide insight as to how much sediment is being produced by the road and where it is being transported (Fu et al., 2010). The following section summarizes various sediment collection techniques used by researchers evaluating erosion processes and sediment production from unpaved roads.

2.6.1 Sediment collection techniques

Sediment collection techniques vary according to the resources available and the type of results required. Ebisemiju (1990) suggests that runoff plots at the field scale are the best way to measure sediment and runoff in developing countries where resources are limited.

In a study done by Ramos-Scharrón and MacDonald (2007a) in the U.S. Virgin Islands, sediment fences were placed at the drainage points of various catchments to measure sediment production within the catchment. The drainage areas of these catchments ranged from 0.9 to 15 ha with average slopes of 15-37%. To specifically measure sediment from unpaved roads, two different methods were used: sediment traps and silt fences. Sediment traps were found to underestimate total sediment production because the traps only retained approximately one-third of the silt and clay sized fractions of sediment (Ramos-Scharrón and MacDonald, 2007a). To use silt fences for unpaved roads, Ramos-Scharrón and MacDonald (2007a) placed fences at drainage points, measuring and weighing the sediment collected after storm events. The silt fences were constructed out of filter fabric and attached to 1-m long pieces of rebar that were hammered into the ground. Sediment production from road cut-slopes was also measured using silt fences that were placed below a road segment so that it could collect sediment from both the road and the cut-slope.

Robichaud and Brown (2002) found in their study that silt fences can retain over 90% of sediment from a catchment. It was determined that the silt fences have trapping efficiencies that range from 68 to 98%. The silt fences work best with flow rates that are equal to or less than 0.013 m^3 sec^{-1} and for contributing areas of less than 1950 m^2. Contributing area can be specifically defined so as to measure sediment in terms of volume or weight per-unit area, or it can simply be defined as a hillslope for which volume or weight per-unit width can be measured. Robichaud and Brown (2002) provide specific instructions on silt fence plot installation and maintenance. Accumulated sediment can be measured for total weight by using a hoe or small hand shovel to collect the sediment into a plastic bucket.

Analysis and interpretation of silt fences is difficult due to the high variability of the data (Robichaud and Brown 2002). The distribution of sediment data is usually not assumed to be normal because it is often skewed to the right and/or contains many zeroes; thus, nonparametric procedures are used for analysis. It is suggested that erosion studies include 5-7 replications for each plot or 9 replications if comparing two treatments.

A study completed by Turton et al. (2004) involving unpaved, rural roads in Oklahoma, sought to collect sediment using sediment collection stations. Each station consisted of a sediment collection trough, pumping sampler to sample water and sediment not caught in the trough, an H-flume, and a rain gauge. Each station was connected to the end of a road segment where water typically runs off to a stream or other outlet. The troughs were filled with landscape fabric to trap sediment and baskets were implemented to collect and weigh the sediment (Turton et al., 2004). The pumping sampler, or ISCO, was used to take automatic water and sediment samples during storm events.

The study completed by Luce and Black (1999) used 1.5 m^3 plastic bins as sediment traps to collect sediment from runoff. Water bars and cross drains were installed along road segments to direct flow to the bins. The bins were placed on load cells for weighing purposes. Based on the research of Luce and Black (1999) they found silt fences to have a trapping efficiency of only 40-60%, whereas an overflowing bin with 1/3 of the volume filled with sediment, had a trapping efficiency of 70-80%.

2.6.2 Direct ground measurements

Anderson and MacDonald (1998) completed a study in the U.S. Virgin Islands, in which they developed the model ROADMOD to estimate and map the annual sediment yield from a road network within a watershed. In order to accurately estimate sediment production from the road, they measured the surface material removed from the road.

To do this, they used a straight edge and laid it across the road surface and measured the cross-sectional area of the rills and/or gullies within the road. It was assumed that this cross-sectional area represented the material removed from the road during heavy traffic and rain events and thus, the amount of sediment transported to a nearby water body. It was noted that this method may underestimate or overestimate the amount of eroded material depending on the degree of road compaction.

In another study by Reid and Dunne (1984), the researchers simply measured sediment concentrations by measuring runoff either directly from the channel or where flow naturally dropped over the edge of the road. In addition, they measured the significance of traffic intensity on the production of sediment by measuring sediment concentration before and after a truck passed over a 200 m long road segment.

Megahan and Ketcheson (1996) measured the amount of sediment transported from road surfaces and cut-slopes by mapping and dividing sediment deposits into measurable areas. The depth of each deposit was measured by taking a soil sample of the core of sediment to the mineral soil. The total volume of sediment deposited was calculated by multiplying the average sediment depth by the area of each deposit (Megahan and Ketcheson, 1996).

2.6.3 Stream measurements

In a study done by Sammori et al. (2004), the production and transport mechanisms of suspended sediment in streams were investigated by measuring electrical conductivity (EC), dissolved oxygen (DO), and water discharge. It was found that the source area of the sediment could be estimated based on water discharge relationships. EC and DO were measured and the phase difference between the two was used to estimate the source of suspended solids based on the source of flowing water into the stream. Water sampling systems were placed at a weir within the catchment and suspended solid concentrations were calculated using the gravimetric method. The results indicated that the main source of suspended solid concentrations was close to, or directly in the stream since the time lag between the rainfall intensity and suspended solid concentration peaks was short; the wet riparian zones along the stream were identified as major source areas.

2.6.4 Runoff measurements

Various studies have used rainfall simulations to measure runoff volume and velocity as well as sediment concentrations in the runoff (Ziegler et al. 2004, Reid and Dunne 1984, Negishi, et al. 2008). Rainfall simulators are a convenient way to measure the many factors relating to sediment production from unpaved roads. In a study by Ziegler et al. (2004), simulations were run on five varying roads to determine both runoff generation and sediment response, as well as the contribution of road maintenance and vehicle traffic to sediment production.

In areas where rainfall simulators were not accessible or convenient, researchers used basic ground methods to calculate runoff volume and velocity. In a study by Rijsdijk et al. (2007), runoff volume was calculated using a volumetric method: a 10-L bucket and a stopwatch. In larger areas, temporary structures such as V-notch weirs were used to measure flow.

2.6.5 Field observations

In situations where direct measurements are difficult to take, a variety of field observations can be substituted to identify the erosion and sediment delivery potential of a road segment. Based on the literature, the following factors contribute to the erosion and subsequent generation of sediment on an unpaved road: traffic, rainfall intensity, surface characteristics, presence or absence of rills, gullies, runoff, and/ sediment deposits, characteristics of the road cut- and fill-slopes, soil characteristics, existing loose sediment, road construction, and slope. The road network should be divided into uniform segments according to slope, surface cover, road dimensions, traffic intensity, and surrounding land use. The goal of field observation is to identify which roads appear to be highly erodible (i.e. highly trafficked, presence of rills and gullies, presence of loose sediment, etc.) and which areas seem susceptible to high sediment delivery (i.e. presence of channels, little vegetation or depositional zones, etc.).

2.7 Geographic Information Systems (GIS)

The use of Geographic Information Systems (GIS) and Remote Sensing have become essential to the analysis of natural resources and watershed management (Bahadur et al., 2009; Kennedy et al., 2009; Wilson et al., 2001). GIS has the ability to account for topographic and climatic variability, as well as other characteristics that may vary across a landscape (Bahadur, 2008; Bhattarai and Dutta, 2008). GIS is a popular method for performing simple calculations across a large area, especially raster GIS (Fernandez et al., 2003). For example, the USLE equation, when applied to a small watershed, can be calculated by hand; however, GIS can apply the USLE to large or multiple watersheds by incorporating rainfall, soil, slope, and management data sets which correspond to each defined cell. This allows sediment production for each cell within a watershed to be calculated (Fernandez et al., 2003). GIS is also useful for delineating watersheds or flow paths for runoff and sediment (Wilson et at., 2001).

2.8 Remote-sensing

Remote Sensing offers a different asset to the field of sediment and erosion prediction. The process of remote sensing uses aerial photography to detect changes in land condition over large areas and time. These photographs can highlight the causes and effects of such patterns of change (Kennedy, et al., 2008). Remote sensing has been used in the identification and study of vegetative characteristics and for natural resource management in general. Rajbhandari et al. (1999) used LandSAT Thematic Mapper imagery for a watershed in Alabama in order to distinguish and calculate the percentage of each land use within the watershed. This information was crucial to the calculation of sediment yield using GIS and the ANSWERS model. Unsupervised or supervised classification of aerial imagery can be performed to separate an image into various land use classes; this can help in making accurate estimations about flow pathways and erosion potential within a watershed. This technology can be applied to watershed management as a means of identifying sources and sinks for sediment and flow pathways. Kennedy et al. (2008) outlines key questions to consider when using remote sensing for natural resource management. First, the user must identify the resource or attribute that will be managed, as well as the types of changes that will be studied. The availability and cost of imagery and reference data must be considered before the project begins. In addition, the amount of confidence required and thus the amount of allowable error must be identified so as to choose appropriate image technologies, resolutions, and processing procedures.

2.9 Research needs

It is recognized that there is a general lack of understanding of erosive processes from unpaved roads and trails and the corresponding impact within a watershed (Akay et al. 2008; Anderson and MacDonald 1998; Bruijnzeel 2004; Nagle et al. 1999; Ramos-Scharrón and MacDonald 2007a, 2007b; Ziegler et al. 2001, 2002). Anderson and MacDonald (2008) specifically bring attention to the need to better understand the relationship between erosion rate and road age, to assess sediment delivery rates from road segments, to assess the impact of traffic on erosion rates, and to determine erosion rates as a function of storm events. Ziegler et al. (2002) highlights the need for research on features of road segments that affect sediment transport processes, such as ruts. This would involve studies on the infiltration capacity, soil hydraulic conductivity profiles, and soil water retention and storage capacity of a road surface, as well as how these characteristics change with depth or surface type. Bruijnzeel et al. (2004) similarly calls for research on roads as well as settlements and how they affect watershed models; specifically, how soil conservation measures affect hydrology and sediment delivery patterns. Harden (1992) recognizes the need for research on unpaved roads to be focused on those trails that are located within agricultural land; more specifically, how erosion from those trails affects crop productivity, and what types of conservation practices can be implemented by farmers.

Nagle et al. (1999) produced a report on the management of sedimentation in tropical watersheds outlining inefficiencies in current erosion studies, as well as key research needs for the future. One of the main problems noted by Nagle et al. (1999) is the inability to highlight problem areas within a watershed because of a lack of data and field measurement. Most of the research in tropical areas is devoted to small watersheds with specific characteristics and thus is not easily translatable to other tropical areas. One related question posed by the authors is that of extrapolating data gained from such small-scale studies. Can the results from a small tropical watershed be generalized to a whole region (Nagle et al., 1999)? Besides the issue of how the data is used, Nagle et al. (1999) points out inefficiencies in how the data is measured. A concern with the USLE method of estimating sediment is that the USLE was not designed to predict sediment yield from an entire watershed, specifically those in the tropics, nor does it take into account the transport of sediment such as deposition and remobilization. Sediment budgets are mentioned as an effective way to identify sediment processes within a watershed, although few have been devoted to tropical areas or have been complete in how they define production, storage, and transport (Nagle et al. 1999). Based on the literature review completed by Nagle et al. (1999), the following three questions were developed as a means to assess a tropical watershed suffering from erosion: 1) “ What is the natural background rate of erosion and sediment movement which can be expected?” ; 2) “What has been the sediment contribution of human activities and how capable are we of controlling them?”; and 3) “What is the potential for storage within the basin of eroded material, whether of natural or human origins?”

The need for better road erosion models has been identified by Elliot et al. (1999b). There is a need for models which illustrate the impact of roads on watershed hydrologic processes and offer tools to prioritize which roads need maintenance, construction, or removal. In addition, Elliot et al. (1999b) suggests research be focused on developing techniques which can minimize sediment transportation from roads or remove roads in such a way as to minimize their long-term impacts. Besides identifying long-term impacts, Luce and Black (1999) suggest the study of the short-term impacts of road maintenance or surface changes, to see how rapidly erosion conditions change.

There has been limited study done on the absolute magnitude of sediment generation rates from individual, unpaved roads (Sheridan and Noske, 2007). Research needs to be focused therefore on the accuracy of field observations and measurements. Also, there needs to be a focus on quantifying the suspended load portion of total sediment production, as well as how sediment production rates affect in-stream water quality (Sheridan and Noske, 2007). Walling (1983) suggests a focus on improving the understanding of sediment delivery and reevaluating the process of estimating sediment delivery ratios. The calculation of this ratio should incorporate an understanding of surface roughness, deposition zones, and the response of cohesive sediments (Walling, 1983). Ebisemiju (1990) also points to the lack of data on sediment sources and delivery in the humid tropics. Understanding sediment delivery at a field scale is important to modeling transport throughout the entire basin. Research should be focused on studying the movement of sediment on cut-slopes within a watershed (Ebisemiju, 1990). Croke (2006) states there has been little work devoted to understanding depositional processes of sediment transportation, specifically in regards to road surfaces. In addition, more work should be focused at the scale of an entire road segment which includes contributions from hillslope and ditches.

One of the biggest needs in the field of watershed management is the assessment of management practices that have been implemented to reduce erosion. The process of erosion has been heavily researched, and models developed to better understand the effect of roads within a watershed, however there has been minimal work on the implementation, monitoring, and modeling of erosion control practices for road erosion.

2.10 Summary

Unpaved roads can be a significant contributor of sediment within a watershed. The slope, infiltration capacity, road dimensions, surface condition, soil type, traffic intensity, and surrounding conditions, all directly affect the type and amount of erosion that occurs. Roads are unique features within a watershed because they can alter the natural hydrology. They can act as links between various sediment sources and streams. Prioritization of road segments which have significant negative effects on the environment can aid in watershed management. A variety of road erosion prediction models have been developed for this purpose; however, most have been developed in the United States and have not been applied to tropical conditions. A universal weakness with these models is the method by which sediment delivery is estimated or calculated. It is important to be able to identify which road segments deliver the most sediment to surrounding water bodies. Research is needed in the application of these models to additional climates and watershed management purposes. In addition, research is needed to improve road management practices in tropical conditions. Once erosive road segments are prioritized, appropriate management practices must be identified and applied.

Chapter 3. Methods

3.1 Model evaluation and selection

A literature review of current erosion prediction models provided a comprehensive understanding of the available approaches to the prediction of road erosion. In order to evaluate whether these approaches were applicable to tropical conditions, a set of criteria were defined to represent the main factors that must be considered when predicting road erosion in the tropics. Erosion prediction factors were identified in the literature and used as the basis for defining this set of criteria.

Each model was evaluated according to the criteria developed; a score of 1 to 5 (poor – best) was assigned for each criterion based on the model's ability to satisfy the requirements of that criterion. A decision matrix was constructed to compare models and select the top three candidate models to apply to the Corrego Horizonte watershed.

3.2 Corrego Horizonte watershed description

A 13 km^2 watershed encompassing the Corrego Horizonte (Horizonte Creek) in Eastern Brazil was chosen as a case study to explore sediment production from unpaved roads and associated modeling approaches (figure 3.1). The predominant landuse is pasture, with cropland, coffee and forest as secondary land uses (figure 3.2). Elevation ranges from 100 to 700 m with soils primarily classified as Oxisols and Inceptisols. The region is characterized by dry winters and rainy summers.

A site visit to the Corrego Horizonte watershed in December 2009 provided the input data for the road erosion prediction models and identified the potential erodibility and sediment delivery from each road segment. The following factors were defined for each segment: road length and width, road slope, surface cover condition, presence of loose sediment on the roadbed, depositional zones, presence of rills or gullies, soil type and texture, percent cover and condition of cut- and fill-slopes, traffic intensity, grading frequency, and the distance from the road to the stream. A handheld GPS was used to track location, to mark key points such as changes in grade and drainage points, and to map elevation change along the road network.

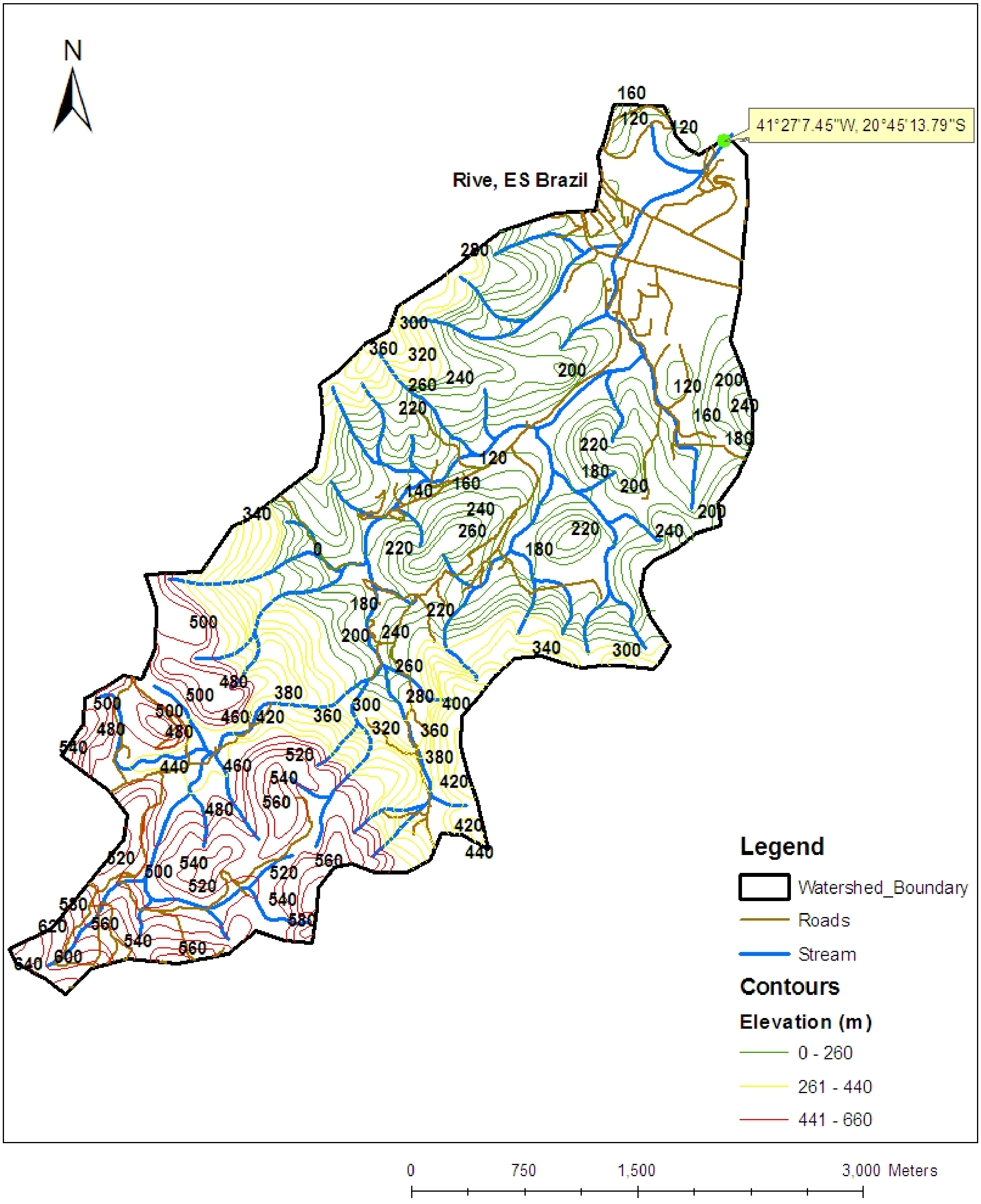

Figure 3.1. Map of Corrego Horizonte watershed depicting the Corrego Horizonte, existing roads, and topographic contours (elevation given in meters). The

outlet of the watershed is located at approximately 41 27' 45" W and 20 45' 13.79" S.

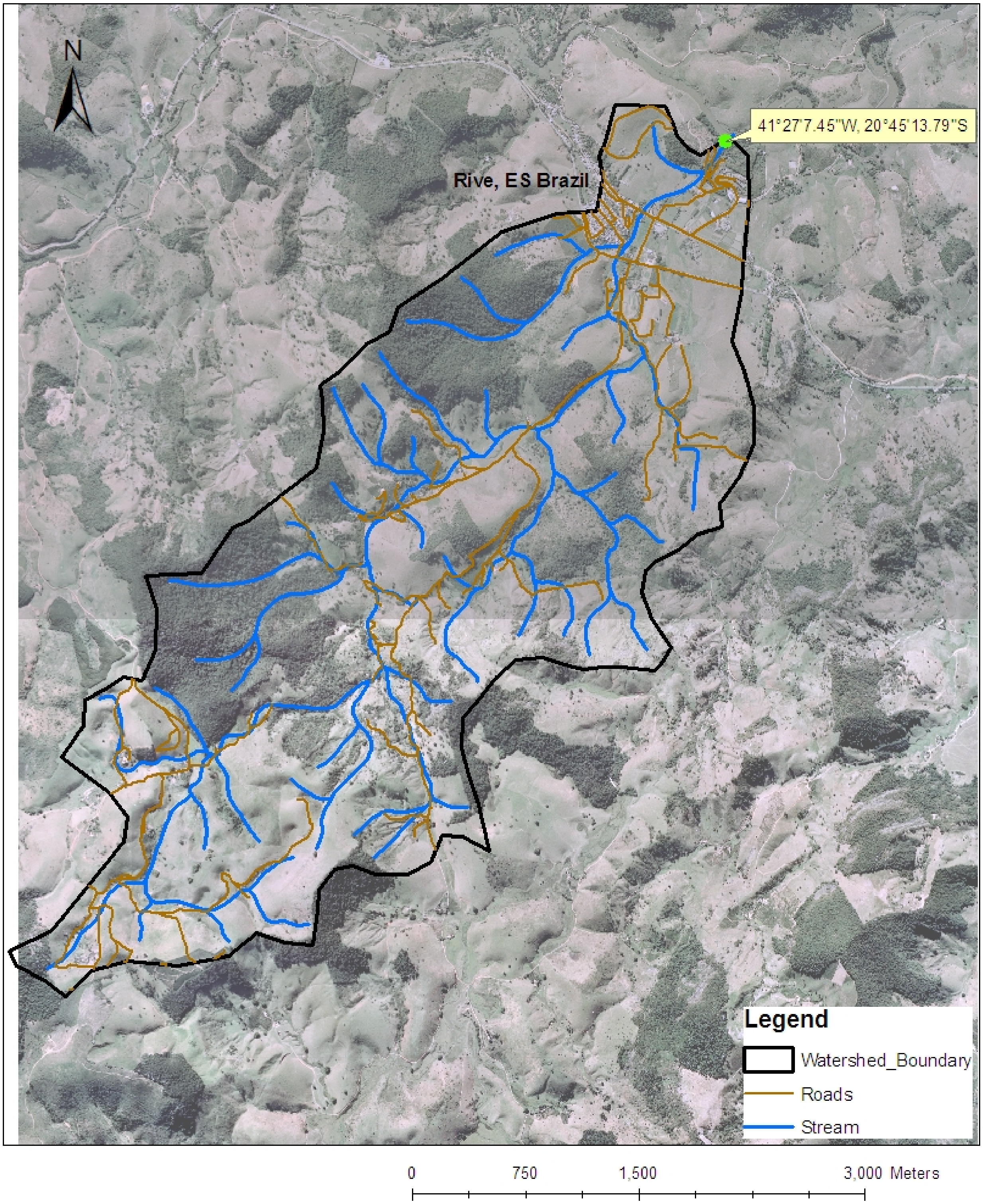

Figure 3.2. Land use in the Corrego Horizonte watershed.

3.3 Model evaluation

Hydrologic and sediment load data are not available for the Corrego Horizonte watershed so model evaluation based on accuracy in predicting absolute sediment loading from the watershed is not possible. Evaluation of model performance was instead based on their ability to identify and rank road segments in terms of sediment generation. The ability of the models to provide an accurate relative ranking of road segments based on predicted severity of erosion was evaluated through comparison with a field-based classification of erosion from each road segment and through comparison between the predictions of WEPP: Road, SEDMODL, and STJ-EROS.

The road network in the watershed was divided into segments having uniform characteristics defined by a unique set of properties pertinent to erosion and sediment delivery to stream (i.e. road design, flow length, surface condition, etc.). These properties define the inputs of the erosion prediction models used to estimate sediment yield. In addition, a field classification system was developed to rank road segments according to the severity of sediment generation and sediment delivery.

Model parameters were defined based on field observations. Each model was then run to estimate sediment yield for each road segment within the watershed. A paired Wilcox test was used to statistically test for significant differences among mean sediment yield predictions. For each model, road segments were ranked based on the magnitude of erosion predicted. A Spearman’s rank test was used to assess the correlation between model rankings. Model rankings were also compared to rankings assigned by the field-based classification. The relative accuracy of each model was assessed by identifying how many road segments received matching scores to those of field observations for segments with a high potential for erosion.

A sensitivity analysis of each model identified the input parameters critical to the estimation of sediment production and sediment delivery. Recommendations for improvement were made based on strengths and weaknesses identified through the model comparisons and sensitivity analyses.

Chapter 4. Results and Discussion

4.1 Model screening

4.1.1 Evaluation criteria

Based on the various factors and approaches needed to predict road erosion, nine criteria were defined to rate each model according to its suitability for application in the tropics.

1) ***Temporal scale:*** The focus of this analysis is on long-term (annual) sediment loading.

2) ***Spatial scale:*** Sediment loading at a watershed scale is desired so that particular road segments with high sediment yields can be identified, yet watershed level impact assessed.

3) ***Representation of erodible features and processes:*** This is one of the most important criteria since the accuracy of representation directly affects model output. The representation of erodible features relates to how sediment sources are identified and modeled; the more sediment sources identified, the more comprehensive the sediment budget. Erosion and delivery processes are modeled through sediment delivery ratios, sediment transportation, and types of road erosion. Model output is affected by the degree of detail and accuracy to which these factors are represented.

4) ***Data requirements:*** One of the challenges in application to tropical watersheds in developing regions is the lack of watershed data. For this study, priority is given to models with simple and readily definable inputs.

5) ***Ability to simulate management practices:*** While not particularly important for this study, the ability to analyze the effects of practices on sediment loading is valuable for future management application of the model.

6) *Applicability to tropical environments:* The model chosen for this watershed must be relevant to a tropical environment. The origin of the model as well as the places and diversities of applications of the model provide an indication of suitability.

7) *Ease of use:* Related to data requirements, the ease of use for each model is important in relation to the location and type of people working with the model. Land managers in developing, tropical regions may not have the time or background required to use complex erosion prediction models.

8) *Level of output:* In order to compare models effectively, the level of output must be similar. In terms of temporal and spatial scale, it is ideal to have models which output annual sediment loading for a road network. Any additional information in regards to runoff or location of highly erodible areas is beneficial.

9) *Assumptions:* Each model makes assumptions to simplify representation, processes, and inputs. The type and number of assumptions affect the quality of results; assumptions relating to climate, topography, road characteristics, and sediment delivery can directly affect the accuracy of sediment loading results for a road network.

A total of seven models were reviewed using the criteria listed above. A decision matrix (table 4.1) based on these criteria provided a means for comparing each model. Each criterion was assigned a weight according to its relative affect on the prediction of road erosion for the Corrego Horizonte watershed. The values were multiplied by the degree of importance and summed to calculate a total score for each model. These scores guided the selection of which models to apply in the Corrego Horizonte watershed for further evaluation.

Table 4.1. Decision matrix for evaluating road erosion prediction models. Matrix values are based on a 1-5 (poor-best) scale representing satisfaction of the criterion. The total for each model is the summation of the score times weight for each criteria.

Criteria	Weight	SEDMODL	ROADMOD	STJ-EROS	KINEROS2	WEPP: Road	WARSEM	SEDD
Temporal Scale	10	4	4	4	3	4	4	3
Spatial Scale	5	4	2	5	2	3	4	4
Representation of Erodible Features	20	3	2	3	4	3	4	3
Data Requirements	15	4	4	4	2	3	3	3
Simulation of Management Practices	5	2	2	2	1	3	5	1
Applicability to Tropical Environments	20	4	4	4	2	3	2	3
Ease of Use	15	3	3	2	1	4	3	2
Level of Output	5	3	3	5	2	3	3	3
Assumptions	5	3	2	2	3	3	2	1
Total weighted score		345	310	340	235	325	325	270

4.1.2 Model selection

The models chosen for application were SEDMODL, STJ-EROS, and WEPP: Road. SEDMODL is a versatile model which can be adapted to most regions because it allows the user to input most site specific information. It only requires two equations and the data for the input parameters are relatively easy to obtain. A revised version of SEDMODL, called SEDMODL2, was created to incorporate Microsoft Access and GIS. SEDMODL2 utilizes the same equations and the same inputs as SEDMODL. The new features of SEDMODL2 include additional inputs of soil depth and bulk density, road design, and drainage structure type and location and a calculation of soil creep from the streams within the watershed (NCASI, 2005). In addition, the geologic erosion rate and rainfall factors were updated. The geologic erosion rate was modified to be represented as a factor and the rainfall factor was updated to distinguish between rain and snow precipitation types (NCASI, 2005). SEDMODL was chosen over SEDMODL2 because a user must purchase SEDMODL2 and the Access/GIS interface may be difficult for a land manager in a developing country to learn and implement. In addition, the interface provided by SEDMODL2 decreases some of the flexibility that is available when using only the equations. Since SEDMODL was developed in the United States, the factors were determined based on conditions from forested roads in Idaho, Oregon, Washington, North Carolina, and West Virginia (NCASI, 2005). The authors of both models caution the users in implementing these equations in other areas (NCASI, 2005). With this in mind, SEDMODL allows the user to adjust those parameters that may be different or not applicable in a tropical watershed.

STJ-EROS was selected because it is one of the few models developed and applied in tropical conditions. The entire model requires many inputs; however, this allows it to present a comprehensive estimate of sediment production from various sources within a watershed. In the case of the Corrego Horizonte watershed, data are not available to use the entire model so only the road algorithm will be applied because it utilizes one equation with three easily defined inputs. WEPP is a relatively well known model, having been applied to a variety of locations and even to road networks within the United States (Rhee et al., 2004; McFero, 2005). Although, WEPP can be used to estimate erosion from a road networks, WEPP was created for hillslope erosion and requires specific inputs describing soil parameters, management activities, and vegetation conditions. WEPP: Road was chosen because it was developed specifically to predict sediment from individual roads and is free and easy to access online. It requires little training or preparation and the input data is easy to acquire. Each model chosen for application to the Corrego Horizonte watershed can be incorporated with GIS and can output sediment loading on a watershed scale for the entire road network. Particularly valuable is the ability to evaluate the erosion potential of each road segment.

4.2 Road division

Each model predicts sediment production based on a single road segment. Therefore the road network must be divided into segments, with each segment uniform in terms of slope, road width, surface cover material and condition, traffic intensity, grading frequency, and road design. The network was first divided based on slope. A handheld 'consumer' GPS with nominal 3-5m accuracy was used in a tracking mode to store location and elevation along the road. Slope was then calculated by dividing the elevation change between the first and last points of a segment by the distance between the two points. In order to verify the accuracy of the GPS measurement of slope, a selection of segments were surveyed using a transit, and point and track slope estimates were compared. The GPS tracks were found to provide an accurate estimate of slope, and these values were used for the subsequent analysis. An explanation of the GPS slope analysis and the results are summarized in Appendix A.

To divide the road network based on slope, the points of each GPS track were graphed to show the road profile: distance (m) vs. elevation (m). Shown in figure 4.1 is the road profile for track 1 taken December 10, 2009. Each road profile was visually observed to note breaks in slope. At those points, a closer inspection of specific track points was used to choose breaks in individual segments.

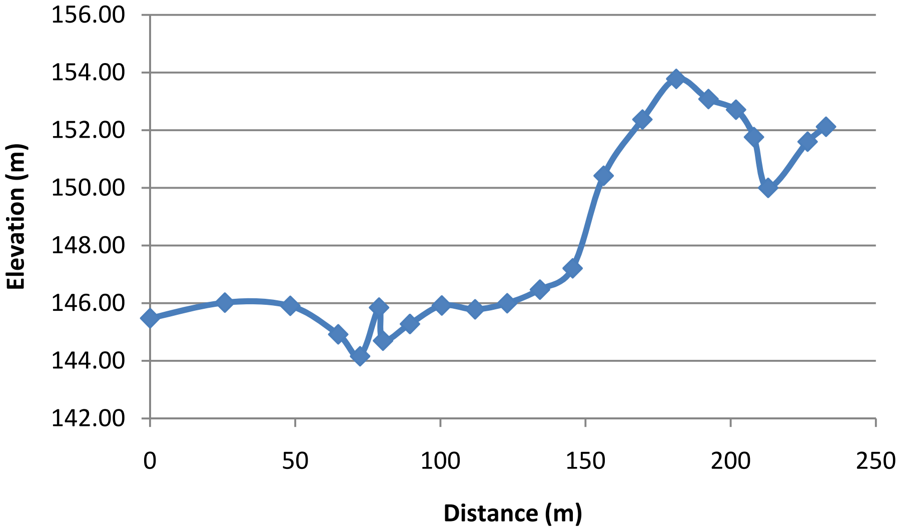

Figure 4.1. Road profile of track 1, points taken December 10, 2009.

Although the slope analysis (Appendix A) showed no statistical difference GPS slopes derived from tracks collected while driving versus walking, driving tracks were chosen over walking tracks. The majority of roads had been documented while driving and the consistent speed maintained while driving resulted in greater uniformity in the point spacing. In cases where driving tracks were not available, points taken every second while walking were used.

After road segments were identified through breaks in the road profile of each track, they were input manually into GIS. By creating a polyline feature, each road segment was manually drawn into a shapefile based on the points chosen from the original track. A total of 90 road segments were identified purely based on slope.

To check the uniformity of road division, pictures assigned to each GIS track were examined to determine visual changes in slope, surface cover condition, cut-slope condition, and distance to the stream. The tracks were further divided based on changes in surface cover condition. Changes included an increase or decrease in the amount of loose sediment, increase or decrease in the distance of the road to the stream, change in condition of cut-slope and/or fill-slope, as well as changes in traffic intensity. In addition, the WEPP: Road model does not allow for any segments over 300 m so those segments longer than 300 m were divided based on slope or road condition depending on the segment. A total of 114 road segments were identified.

Once segments were divided, the slope of each road segment was calculated by dividing the change in elevation between the first and last point of the segment by the length of the segment. Segment 24 had a calculated slope of 0%. In order to run the WEPP: Road, which accepts values of road slopes ranging from 0.1 to 40%, this value was reassigned a value of 0.1% (Elliot et al., 1999c). The road length and width were measured at various segments throughout the watershed and applied throughout the rest of the road network. Figure 4.2 presents a histogram of road segment lengths in the Corrego Horizonte. Figure 4.3 depicts the slopes associated with various road lengths.

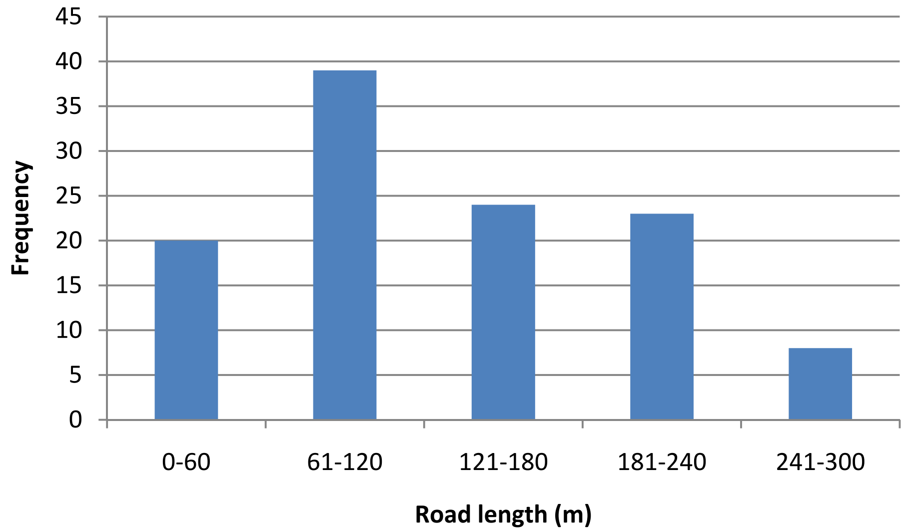

Figure 4.2. Histogram of road segment lengths (m) in the Corrego Horizonte road network.

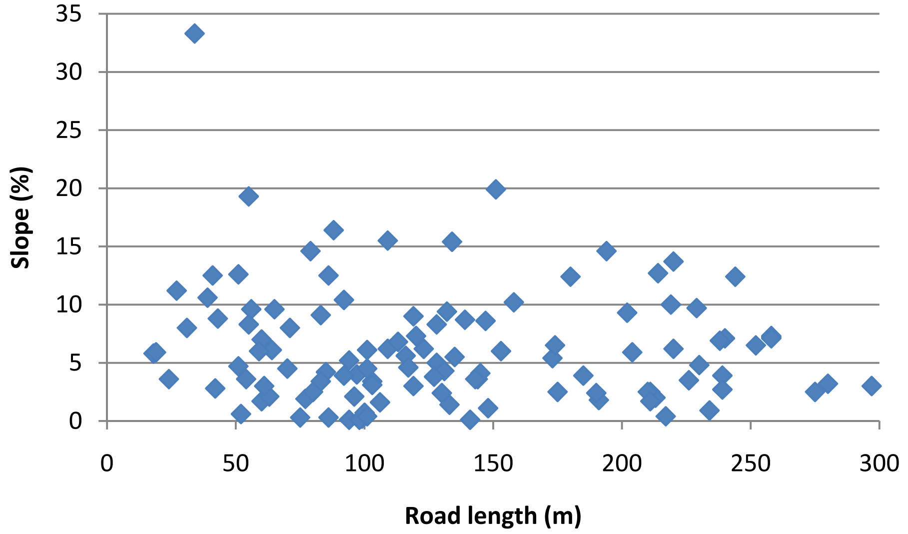

Figure 4.3. Scatterplot of road length (m) versus slope (%) from road segments within the Corrego Horizonte watershed.

Using the field notes and photos taken from December, attributes were assigned to each segment. The following attributes were characterized: surface description, traffic intensity, road design, distance to stream, cut-slope and fill-slope condition, grading frequency, ditch condition, and drainage condition. Road surface description was based on the degree of compaction of the roadbed, the soil type (clay vs. sand, Oxisol vs. Inceptisol), amount of loose sediment, and the presence of rills and/or ruts. Traffic intensity was determined based on personal observation over the course of the ten day field visit and conversations with the local inhabitants. Intensities ranged from high to very low; high representing the main travel way and very low representing trails used by one household and/or cattle. Distance to the stream was estimated by fill-slope and buffer lengths. The road design was determined to be crowned, outsloping, or insloping based on field observations and photos. The cut-slope and fill-slopes were noted for their corresponding slopes and percentage of vegetative cover. Grading was concluded to be either infrequent or frequent based on the visual observation of road maintenance. Ditch and drainage conditions were noted simply for presence and condition (poor vs. stable). A summary of road segments and their associated characteristics can be seen in Appendix B, tables B.1, B.2, and B.3.

4.3 Field classification of road segments

High erosion potential of roads can be defined by steep slopes, evidence of high flows, ruts, erodible cut-slopes, and loose sediment on the roadbed (Luce and Black, 1999; Vanacker et al., 2007; Ebisemiju, 1990; Ziegler et al. 2004). Roads with high sediment delivery are generally those roads with a close proximity to a water source, concentrated drainage, and poorly vegetated fill-slopes. These characteristics can be used to identify which road segments could lead to environmental degradation of the watershed, and thus target roads requiring management. To define the environmental impact of a road segment, a classification system was developed to categorize road segments according to two factors: sediment production and sediment delivery. These factors were further broken down into criteria which could be used to describe the relative potential (low to high) of each factor. The classification system was used to score road segments using field observations and model output. The relative rankings of each model were compared to each another as well as to rankings assigned from field observations for each road segment.

4.3.1 Sediment production potential

To evaluate a road segment in terms of sediment production, two criteria include runoff characteristics and the amount of sediment available for transport. Runoff characteristics relate to the volume and velocity of flow in the roadway; the higher the volume and velocity of the flow, the higher the erosive energy and transport capacity of runoff (Luce and Black, 1999). Catchment area is a function of characteristics of the road profile, specifically measuring slope, distance between drainage points, and width (Hairsine et al., 2002). The presence of rills and ruts on the road bed, erosion of the ditch if present, and places of active erosion generally indicate the existence of erosive flow. The amount of sediment available for transport can also signify the potential for sediment production for a road segment. Loose sediment can result from grading and repair, traffic, erodible soils, areas upslope which drain to the segment, an eroding cut-slope, or from the roadbed or ditch. The significance of these sources, indicate the stability of the roadbed, cut-slope, and connecting roads. Areas with active erosion, loose, fine sediment particles, or ruts and gullies generally represent sediment sources. The traffic intensity or grading frequency of the road segment are also good indicators of whether the road segment provides sediment for transport; the higher the traffic intensity and/or grading frequency, the more potential for sediment generation. Road segments with native surface materials such as clay and sandy soils will generate more sediment than those with gravel (Elliot et al., 1999a). Figure 4.4 illustrates examples of road segments with various amounts of loose sediment available for transport, ranked very high to low.

Figure 4.4. Examples of road segments classified from very high to low (clockwise) in terms of sediment availability.

In order to classify the sediment production potential of a road segment, each criterion was divided into a series of four rankings representing worst to best case conditions. This classification method is by no means comprehensive; it is difficult to represent every combination of road characteristics in a variety of climates and locations. These descriptions are general and may not apply in all situations; final judgment of road condition is left up to the observer or land manager. The following descriptions were used as a guide in ranking segments according to their runoff characteristics and sediment availability.

Runoff characteristics

> ***Very high***: Road segments with the potential for very high runoff volume and velocity are typically roads with steep slopes (>10%). Steep slopes will increase the velocity of runoff and the energy to detach and transport sediment. A long flow path can also contribute to high volumes of runoff; roads with lengths greater than 200 m may be indicative of very high runoff volumes and velocities

as there more time for water accumulation on the surface (Elliot et al., 1999a). Flow path is determined by the distance between drainage points or the distance along a road segment where the majority of flow travels before draining off the road (i.e ruts or ditches). These roads typically have irregular drainage. As a result, numerous ruts and rills will be present on the road surface indicating the flow path of runoff. The width and depth of ruts and rills can indicate the volume and velocity of flow.

High: Road segments with the potential for high runoff volume and velocity have moderate slopes of 5 – 10% and/or a flow path of 100 – 200 m. These roads will also have a poor road structure with flow dispersed across the road surface. A ditch may be present, but little to no flow is directed and dispersed in this manner. Ruts and rills are present on the road surface, but will be fewer in number and smaller in size.

Moderate: Road segments with moderate runoff velocity and volume have lower slopes of 2 – 5% and/or moderate flow paths of 50 – 100 m. A good road structure will divert flow to regularly spaced drainage points or a ditch. Although rills may be present, the volume and velocity of runoff is not high enough to generate ruts.

Low: Road segments with low runoff volumes and velocities have low slopes of 0 – 2% and/or short flow paths of 0 – 50m. Roads structure is stable and diverts flow to regular drainage points and/or a ditch. There are no ruts and few rills present.

Sediment availability

Very high: Road segments with a large amount of sediment available for transport have active erosion visible on the roadbed. The majority of the road surface (>50%) is covered by fine, loose sediment particles. These segments experience high traffic intensity and typically have erodible parent materials making them susceptible to erosion. The cut-slope is unstable with little to no vegetative cover with evidence of active erosion. These segments may regularly undergo grading or repair; grading and/or repair involves the addition of sediment to fill ruts or reconstruct road structure, thus providing a large amount of sediment to be transported during precipitation events.

High: The road surface is approximately 30 – 50% covered in fine, loose sediment particles with active erosion only evident in a few places on the roadbed. Traffic intensity may range from moderate to high. The cut-slope is stable with low to moderate vegetative cover and little to no sign of active erosion. Road segments with high amounts of available sediment may have occasional grading or repair (once every 1 – 2 years).

Moderate: Approximately 10 – 30% of the road surface is covered by fine, loose sediment particles and there is no active erosion of the roadbed. These road segments receive lower traffic use and the cut-slopes are stable with sufficient vegetative cover. Roads with a moderate amount of available sediment have no grading of the road.

Low: Less than 10% of the road surface is covered by fine, loose sediment particles and there is no erosion of the roadbed. Cut-slopes are stable with good vegetative cover. Roads with a low to negligible amount of sediment available for transport have no grading of the road and receive very low traffic use.

4.3.2 Sediment delivery potential

Sediment delivery is another important component used to evaluate the environmental impact of a road segment. The two criteria used to determine sediment delivery potential include the distance of the road segment to a nearby stream and the condition of the delivery pathway. The effect of distance of the road to the stream is clear: the closer a road is to a stream, the more likely sediment transported by runoff will reach the stream. Figure 4.5 illustrates an example of a visible pattern of direct deposit of sediment from a road segment to a stream. Distance alone cannot determine the degree of delivery, as the condition of the pathway can indicate whether any or all of the sediment is deposited along the way. Condition of the pathway is defined by vegetative cover, soil type, land management, slope, and drainage condition. Drainage points tend to concentrate flow, and if not spaced adequately, can divert the majority of runoff from the road to the stream; in these situations runoff velocity and volume are high and may have enough energy to not only travel long distances, but also to erode the soil along the way. Evidence of flow patterns can point to where runoff travels and if it slows down enough to deposit sediment. Land management can significantly reduce sediment delivery to a stream. By simply maintaining good vegetative cover for example, velocity and volume of flow can be reduced. Areas with low slopes and vegetation can act as sediment traps.

Figure 4.5. Example of direct delivery of sediment from a road segment evident by the flow patterns.

The models evaluated in this study do not contain specific equations or algorithms to determine the sediment delivery characteristics of each road segment. For those models requiring a sediment delivery ratio, it is up to the judgment of the user to specify how close the road is to the stream. Therefore, any evaluation of sediment delivery would be biased as it would be impossible to compare the user’s opinion to anything else. Nonetheless, sediment delivery is an important component to consider when evaluating the environmental impact of a road segment. The following descriptions of distance and delivery pathway conditions can be used as a guide to ranking a road segment according to its potential for sediment contribution to nearby streams or water bodies.

Distance of road to stream

Very high: A road segment with very high sediment delivery is generally within 10 m of a stream. There is evidence of direct deposit and it is clear that the majority of runoff traveling along the road is dispersed to the stream. Often, these road segments cross over a stream.

High: High sediment delivery occurs on road segments that are 10 – 20 m from a stream.

Moderate: Road segments with moderate delivery are typically 20 – 60 m from a stream. Generally there is enough distance between the road and the stream such that the runoff has time to slow and deposit the majority of sediment.

Low: Low delivery occurs on road segments that are generally greater than 60 m from a stream.

Condition of delivery pathway

Poor: Poor delivery pathways are characterized by steep slopes (>10%) and little vegetation ranging from 0 – 25% cover. There is visible erosion or evidence of high flow through drainage points. In addition, there are poor land management practices leading to active erosion of the fill-slope.

Fair: A delivery pathway in fair condition has moderate slopes of 5 – 10% and is typically 25 – 50% vegetated. There is high flow through drainage points but little evidence of erosion. Land management is such that it does not affect the condition of the fill-slope in any way.

Good: A good delivery pathway has moderate slopes of 5 – 10% but is covered by 50 – 75% vegetation. There is less flow directed through drainage points and little to no erosion of the fill-slope.

Excellent: Delivery pathways in excellent condition are characterized by low slopes of less than 5% and vegetative cover of 75 – 100%. There is no erosion of drainage points or the fill-slope itself. Land management utilizes practices that protect the soil from erosion.

4.3.3 Classification results

To evaluate the road network within the Corrego Horizonte watershed, each segment was classified in terms of sediment production potential and sediment delivery potential. Each road segment was ranked from low to very high according to runoff characteristics and sediment availability. Table 4.2 assigns a final score of 1 to 5 (1 = low, 5 = very high) for each combination of rankings; this final score represents the severity of the road segment as a source of sediment. Table 4.3 is a similar table used to classify a road segment in terms of its sediment delivery potential.

Table 4.2. Classification of the sediment production potential of road segments as a function of runoff characteristics and sediment availability. Score of 1 represents low sediment production potential; score of 5 represents very high sediment production potential. (Description of criteria given in the text).

	Runoff rate and volume			
Sediment Availability	Very high	High	Moderate	Low
Very high	5 (5)*	5 (0)	4 (0)	3 (0)
High	5 (4)	4 (6)	3 (3)	2 (0)
Moderate	4 (2)	3 (14)	2 (7)	1 (8)
Low	3 (3)	2 (9)	1 (24)	1 (29)

*****Number in parentheses represents the number of road segments in that category

Table 4.3. Classification of the sediment delivery potential of a road segment as a function of distance of road to stream and delivery pathway condition. Score of 1 represents low delivery potential; score of 5 represents very high delivery potential. (Description of criterion given in the text).

Condition of delivery pathway	Distance of road segment to stream			
	Poor: direct	Fair: close	Good: far	Best: very far
Poor	5 (1)*	5 (1)	3 (0)	2 (0)
Fair	5 (2)	4 (1)	3 (7)	2 (5)
Good	4 (1)	3 (13)	2 (14)	1 (21)
Best	3 (6)	2 (19)	1 (2)	1 (21)

*Number in parentheses represents the number of road segments in that category

The purpose of a five point scale for each factor is not to identify the 'worst' road segment, but rather a group of segments for which management would be appropriate. Roads with final scores of 4-5 are considered to have high erosion or delivery potential, while those with scores of 2-3 have moderate to low potential, and segments with a score of 1 have very low potential. A combination of the sediment production and sediment delivery scores could be used to evaluate the overall environmental impact a road segment has on a watershed.

In this study, the models output an estimate of sediment yield from each road segment and do not include an estimation of sediment delivery; thus no comparison of sediment delivery can be made between models and field observations. The classification system described above was used to assign a final score to each road segment according to its sediment production potential. The similarities and differences between field rankings and model rankings were main factors used in determining the applicability of each model to the Corrego Horizonte watershed.

4.4 Model analysis

4.4.1 WEPP: Road

Before running the WEPP: Road model, the climate parameters were adjusted using The Rocky Mountain Climate Generator (Rock: Clime) provided by the developers of the WEPP models, to fit the characteristics of Rive, Brazil (Elliot et al., 1999c; USDA, 2009). Since no current weather data exists for the Corrego Horizonte watershed, weather data from the nearby town of Alegre, as summarized in table 4.4 (Insituto Capixaba de Pesquisa, Assistência Técnica e Extensão Rural, 2009). The watershed outlet was assigned coordinates of 20.75°S and 41.45°W, along with an average elevation value of 200 m. The Key West, Florida dataset provided by Rock: Clime was modified using these values. The climate data is used to estimate storm events and calculate subsequent infiltration and rainfall excess across the surface each day (Elliot et al., 1999c).

Table 4.4. Summary of weather data for Alegre, ES Brazil

Month	Mean Maximum Temperature (°C)	Mean Minimum Temperature (°C)	Mean Precipitation (mm)	Number of Wet Days (days)
January	32	21	200	17
February	33	21	125	14
March	32	21	140	15
April	29	19.5	105	16
May	28	17	50	8
June	27.4	16	15	8
July	27	15	20	5
August	28.5	16	25	6
September	29	17	55	7
October	30	19	105	10
November	30.5	20	200	18
December	31	21	250	19
Annual			1290	143

The model was set to run the data for a one year period. The soil texture chosen was clay loam. The rest of the input parameters include: road design, road surface type, traffic level, road gradient, road length, road width, fill gradient, fill length, buffer gradient, buffer length, and percent rock fragment.

The road design options include: “insloped bare ditch”, “insloped vegetated or rocked ditch”, “outsloped rutted”, and “outsloped unrutted.” WEPP: Road does not provide an option for crowned roads. Instead it suggests assuming insloped if there are no ruts or outsloped if ruts are present; the road width then includes the width of the ditch (Elliot et al., 1999c). In the Corrego Horizonte watershed, the majority of roads are “outsloped rutted”. WEPP: Road assumes these roads have ruts greater than 10 mm, spaced 2 m apart (Elliot et al., 1999c). The remaining roads are classified either as "outsloped unrutted" or "insloped bare ditch". Outsloping, unrutted roads are assumed to have ruts less than 10 mm spaced at 1 m intervals (Elliot et al., 1999c). WEPP: Road assumes insloping roads with a bare ditch have rills spaced 4 m apart and a well maintained ditch, through which all flow travels (Elliot et al., 1999c). Observations indicated that none of the roads classified as insloping have regularly maintained ditches (most were filled with deposited sediment) and the majority of flow did not appear concentrated in the ditch. In addition, for insloping roads with wheel ruts, WEPP: Road suggests classifying the road as "outsloped rutted" (Elliot et al., 1999c). As a result, the insloping segments were reclassified as "outsloped rutted." A total of 46 road segments were classified as "outsloped unrutted" and 68 segments classified as "outsloped rutted."

All road segments were considered to have a native road surface; other options included gravel or paved. All roads are assumed to have no surface vegetation (Elliot et al., 1999c). WEPP: Road characterizes traffic intensity based on data from forested logging roads. High traffic is assumed to represent roads that bear logging traffic throughout the year, whereas low traffic roads are those limited to administrative purposes during dry weather (Elliot et al., 1999c). No traffic roads are those with restricted access and may have vegetation present on the surface (Elliot et al., 1999c). Since these assumptions are generally not valid for the Corrego Horizonte watershed, high traffic was applied to those roads bearing the majority of traffic (i.e 70% or more). Low traffic was applied to all other roads and no traffic was applied to one segment which appeared abandoned due to the significant amount of vegetation present on the road surface as well as the multiple gullies across the road width (figure 4.6). A total of 43 segments were considered high traffic roads, 70 roads were considered to carry low traffic levels, and one road was classified as having no traffic.

Figure 4.6. Road segment classified as ‘abandoned’ due to significant erosion and multiple gullies.

WEPP: Road makes assumptions regarding the condition of the fill-slope and buffer between the road and the stream. It assumes the fill-slope is covered by 50% vegetation, and the buffer condition is characteristic of a 20-yr old forest (Elliot et al., 1999c). Fill and buffer slopes were not directly measured in the field. Values were estimated based on field notes and photographs. WEPP: Road accepts fill slopes ranging from 0.1 to 150% and buffer slopes ranging from 0.1 to 100% (Elliot et al., 1999c). For relatively flat areas near the stream or at stream crossings, values of 0.5% were used for the fill or buffer slope. The model accepts fill lengths from 0.3 to 100 m and buffer lengths from 0.3 to 300 m (Elliot et al., 1999c). Fill length was determined based on visual and photographic observations of the distance from the road to the stream. A value of 0.5 m for the fill length was entered at stream crossings. Buffer conditions were generally not present on the majority of roads; however in the forested areas of the watershed, appropriate buffer lengths and gradients were included as inputs. In cases where a buffer was not present, a length of 0.3 and a slope of 0.1 were used (the model does not accept values of 0 for these inputs).

The majority of road segments had a negligible percentage of rock fragments. A total of five segments were identified as having visible rock fragments in the road bed and were given values ranging from 1-5% (figure 4.7).

Figure 4.7. Example of road segment with portion of rock fragments greater than 0%.

WEPP: Road batch allows the user to input more than one road segment. Microsoft Excel was used to organize the input parameters for use by WEPP: Road batch. Outputs include average annual runoff (mm), average annual sediment leaving the road (kg), and average annual sediment leaving the buffer (kg) for each segment. It is assumed that the amount of sediment leaving the buffer is the actual amount of sediment reaching the stream as a portion of the sediment leaving the road is deposited along the fill-slope and buffer. The model provided output for one year and was converted to tons/year.

A summary of sediment yield from each road segment is shown in figure 4.8. WEPP: Road predicted segment 16 to have the highest sediment yield at 52 t/yr. The segment with the lowest estimated sediment yield was segment 92 at 0.006 t/yr.

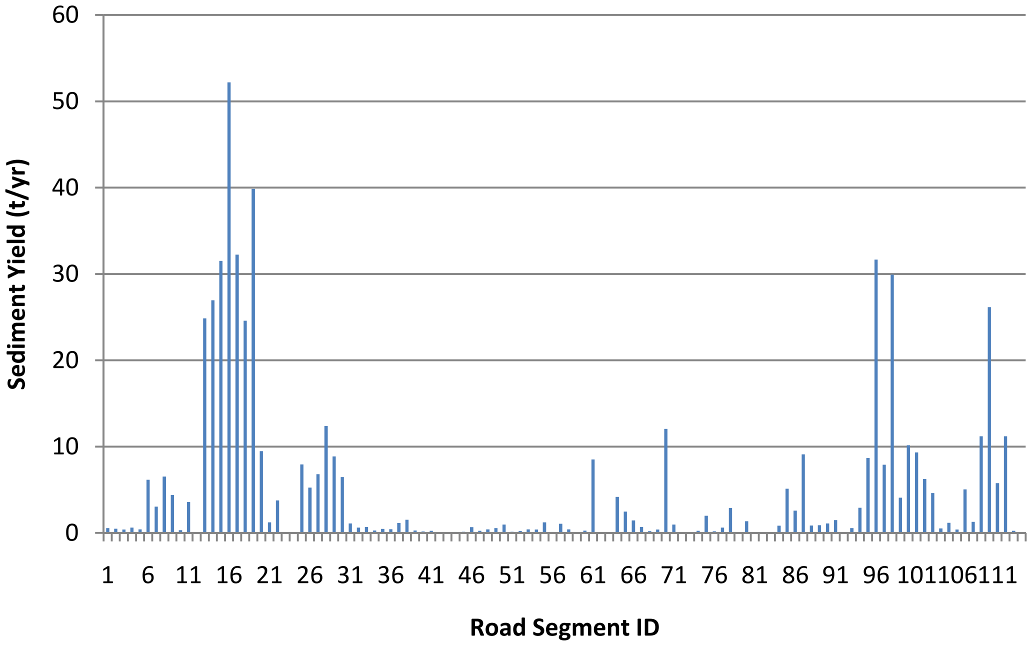

Figure 4.8. Total sediment yield (t/yr) for the Corrego Horizonte watershed as predicted by WEPP: Road.

4.4.2 SEDMODL

SEDMODL calculates sediment yield from the road surface and cut-slope. Total sediment is the sum of these yields multiplied by a road age factor. To calculate total sediment produced from each landscape element, three linear equations are used.

The following equation is used to predict total sediment production in t/yr:

$$Total\ Sediment = (TS + CS)A_f\ , \qquad (4.1)$$

where TS is tread sediment (t/yr), CS is cut-slope sediment (t/yr), and A_f is road age factor. Age factor is assigned a score of 10 if the road was created or graded within the year and assigned a score of 2 for two years or more. The tread sediment is calculated based on the equation:

$$TS = L_r W_r G E_r S_f T_f G_f P_f D_f\ , \qquad (4.2)$$

where L_r is road length (m), W_r is road width(m), GE_r is geologic erosion rate(t/ha/yr), S_f is road tread surfacing factor, T_f is traffic factor, G_f is road grade factor, P_f is precipitation factor, and D_f is sediment delivery ratio. The cut-slope sediment is calculated with the equation:

$$CS = GE_r CS_f CS_h L_r D_f \ , \tag{4.3}$$

where CS_f is cut-slope factor and CS_h is cut-slope height.

According to SEDMODL, tread sediment is based upon road dimensions, a geologic erosion rate, road surface, traffic intensity, slope, precipitation, and sediment delivery. The only inputs associated with units are length (m), width (m), and the geologic erosion rate (t/ha/yr) as provided in a table in the work of Akay et al. (2008). Erosion rate depends on the lithology and geologic age of the sediment. The area within the Corrego Horizonte watershed can be described as having a metamorphic lithology of the Precambrian age. The remaining inputs are assigned factors based on tables provided by the SEDMODL methodology (Akay et al., 2008; NCASI, 2005). Road gradient is assigned a factor based on three categories: less than 5%, 5-10%, and greater than 10%. The majority of road segments have a slope of less than 5%. Road surface options include asphalt, gravel, pitrun, grassed native, native surface, and native with ruts. All roads were assigned either native surface or native with ruts. Traffic intensity is divided into seven categories: highway, main haul, county road, primary road, secondary road, spur road, and abandoned (NCASI, 2005). Each category is based on the degree and type of use. Highway and main hauls are associated with heavy log traffic (>5 log trucks/day and >5 cars/day); county roads receive heavy residential and truck use (1-4 log trucks/day and >10 cars/day); primary roads are those coming off the main road which receive moderate to heavy use (1-4 log trucks/day and 5-10 cars/day); secondary roads receive mainly residential use (<1 log truck/day and 1-5 cars/day); spur roads are short access roads to logging areas (<1 log truck/day and <1 car/day); and abandoned roads are blocked and not used by traffic (NCASI, 2005). Since this watershed does not currently house any logging operations, these descriptions do not accurately apply. The main roads receiving the majority of traffic were assigned to the primary road class as they receive heavy to moderate use.

Roads branching off of this main road were classified as secondary roads. Smaller roads linking farms to secondary roads were classified as spur roads. One road segment was classified as abandoned as it appeared untraveled by vehicles and only cattle (figure 3.9); this segment was also classified as having no traffic in the WEPP: Road model. Average annual precipitation was approximated as 1290 mm (from figures 3.7 and 3.8) and recalculated into a precipitation factor using the following equation given in the SEDMODL methodology (Akay et al., 2008):

$$P_f = (\frac{P_{avg}}{1524})^{0.8} \tag{4.4}$$

where P_{avg} is the average annual precipitation in mm.

Cut-slope sediment depends on road length, cut-slope cover and height, erosion rate, and sediment delivery. The cut-slope cover is defined by the percentage of vegetation covering the slope area; percentages range from 0-100% with a factor for each (Akay et al., 2008; NCASI, 2005). The majority of cut-slopes were considered to be 100% vegetated. Cut-slope height is grouped into four categories based on slope: 0-15%, 15-30%, 30-60%, and greater than 60% (Akay et al., 2008; NCASI, 2005). Nearly all cut-slopes had a slope of 1:1 and were classified as having greater than 60% slope.

A factor for sediment delivery was multiplied to both the tread and cut-slope sediment predictions. The model suggests assigning a factor of 1 if the stream is less than 30 m from a stream, a range of 0.35-0.1 if the road is 30-60 m away from the stream, and 0 if the road is greater than 60 m from the stream (Akay et al., 2008; NCASI, 2005). In this case, a factor of 0.35 was assigned to all cases where the road was 30-60 m to the stream. The distances of the road to the stream were used from the input of fill-slope and buffer length in WEPP: Road. It is unrealistic to assume that no sediment is delivered to the stream if a road is much farther than 60 m from the stream. As noted during field observations, water channelizes during rain events; this results in higher velocities and farther traveling distances. In order to compare and rank road segments in terms of sediment production, a factor of 0.05 was assigned to roads greater than 60 m from a stream.

The sediment yields estimated for each road segment by SEDMODL are summarized in figure 4.9. SEDMODL estimated segment 87 to have the highest sediment yield at approximately 47 t/y. The segment estimated to yield the least amount of sediment was road segment 56 at 0.02 t/yr.

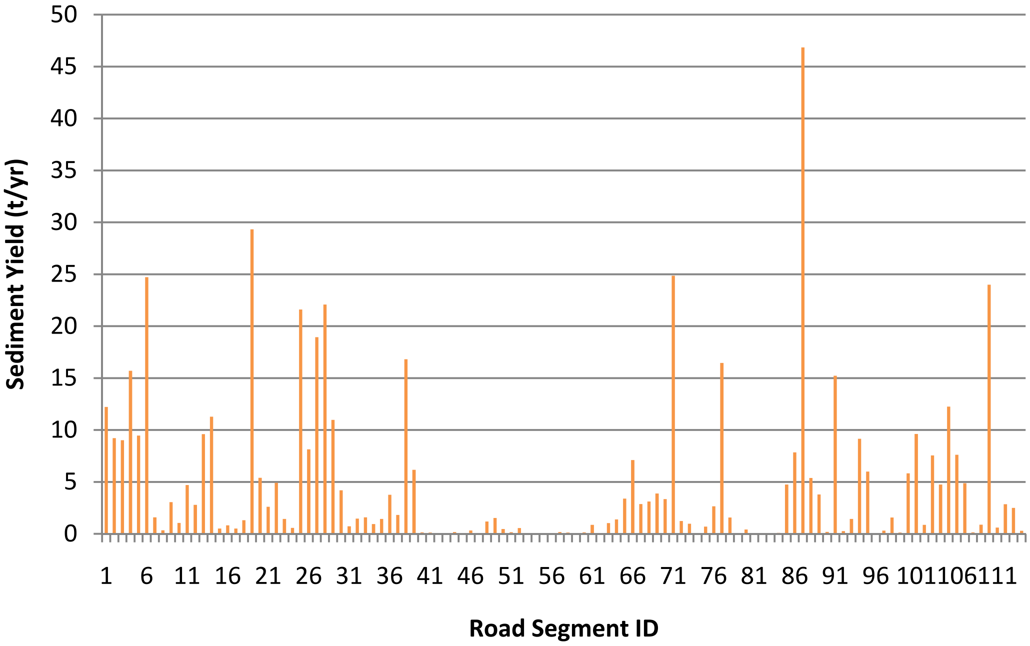

Figure 4.9. Total sediment yield (t/yr) for the Corrego Horizonte watershed as predicted by SEDMODL.

4.4.3 STJ-EROS

The road algorithm for the STJ-EROS model includes equations for both graded and ungraded roads. The equations for graded (S_G) and ungraded (S_{UG}) roads are the following:

$$S_G = [-0.432 + 4.73 * s^{1.5} * r] * L * W * \{1 + 3.4 * 0.06\}\ , \tag{4.5}$$

$$S_{UG} = [-0.432 + 1.88 * s^{1.5} * r] * L * W * \{1 + 3.4 * 0.04\}\ , \tag{4.6}$$

where s represents slope (dec), r represents annual rainfall (cm), L represents road length (m), and W represents road width (m). The rest of the coefficients are developed based on site characteristics from the St. John Virgin Islands. The equations also include the percentage of silt expected from the sediment yield. For ungraded roads, 4% silt is expected, whereas 6% is expected for graded roads. The equations are applicable for slopes ranging from 1% to 21%. In this watershed, some road segments have calculated slopes of less than 1%; this results in a negative sediment yield. As a result, those segments that had a slope of less than 1% were reassigned a slope of 1%. Despite this correction, 13 road segments still had negative sediment yields. These road segments were assigned a final sediment loading value of 0 t/yr. All roads are assumed ungraded since there does not appear to be a regular, if any, maintenance schedule. STJ-EROS assumes graded roads to be graded at least once every two years (Ramos-Scharrón et al., 2007). The final sediment yield is multiplied by the sediment delivery ratio which is entirely up to the user. The percent of sediment delivered to the stream from each road segment assumed in SEDMODL was applied to STJ-EROS to reduce variability during comparison.

STJ-EROS assumes that 91% of the sediment yield from the road comes from these equations and the other 9% come from cut-slope erosion (Ramos-Scharrón et al., 2007). The model assumes that sediment production from the cut-slopes is 9% of that produced by the road surface (Ramos-Scharrón et al., 2007). Total sediment traveling to the stream is therefore the sum of sediment produced by the road and cut-slope areas (kg/yr).

Figure 4.10 summarizes the sediment yields from the Corrego Horizonte watershed as estimated by STJ-EROS. The highest producing road segment is 87, estimated to yield approximately 17 t/yr. STJ-EROS was unable to truly identify a segment with the lowest estimated sediment yield since 13 segments had negative sediment yields. The segments with the lowest estimated yields had values of 0 t/yr.

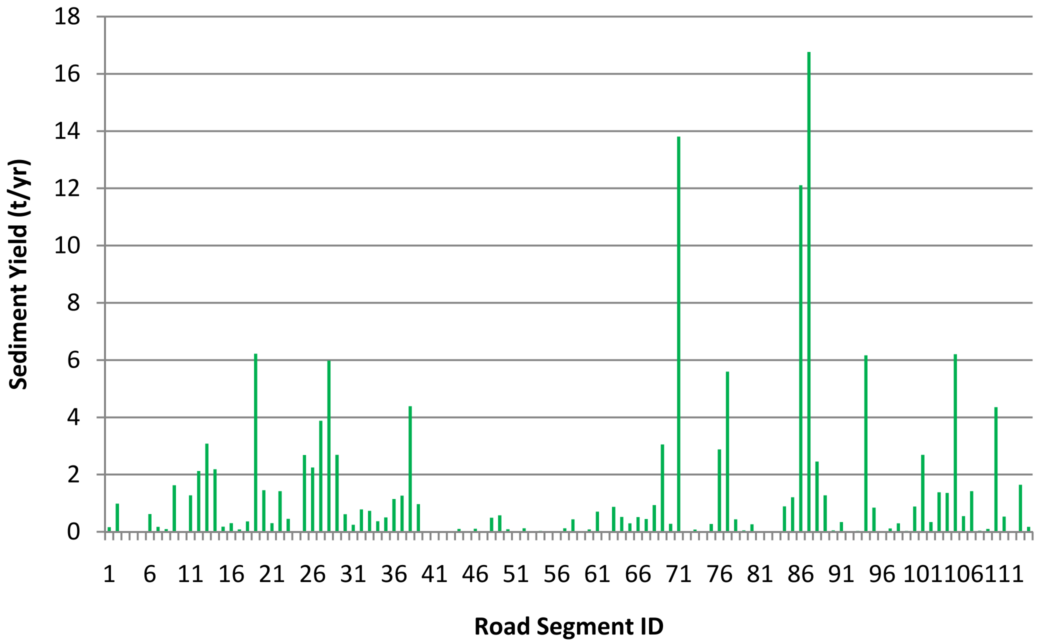

Figure 4.10. Total sediment yield (t/yr) for the Corrego Horizonte watershed as predicted by STJ-EROS.

4.5 Model comparison

The outputs of each model were compared to determine if there was a significant difference in the mean estimated amount of sediment produced from each road segment within the Corrego Horizonte watershed. The null and alternative hypotheses were as follows:

$H_O: \mu_{\mathrm{A}} = \mu_{\mathrm{B}} = \mu_{\mathrm{C}}$: There is no significant difference between the mean estimated sediment yields from the road segments as calculated by SEDMODL (μ_A), WEPP: Road (μ_B), and STJ-EROS (μ_C).

$H_{\mathrm{A}}: \mu_{\mathrm{A}} \neq \mu_{\mathrm{B}} \neq \mu_{\mathrm{C}}$: There is a significant difference between the mean estimated sediment yields from the road segments as calculated by SEDMODL (μ_A), WEPP: Road (μ_B), and STJ-EROS (μ_C).

Model outputs were given in kg/yr, converted to tons/year, and first tested for normality. Since each data set had 114 observations, a Shapiro Wilks normality test was performed on each data set with an alpha of 0.05. All p-values were less than the stated alpha of 0.05, leading to the rejection of the null hypothesis that the data follows a normal distribution. A Fligner-Killeen test was used to test for equal variance. A p-value of 8e-11 was found; this is less than the stated alpha of 0.05, leading to the rejection of the null hypothesis that the data sets have equal variance.

To compare the means of the sediment outputs to determine if they were significantly different, a nonparametric, paired Wilcox test with a Bonferonni fix (alpha of 0.017) was applied. The data was considered paired since each sediment output is dependent on location. Q-Q plots were used to test the assumption that each data set was from the same distribution. Figure 4.11 shows that the data when transformed logarithmically follow a linear trend, indicating they come from the same distributions.

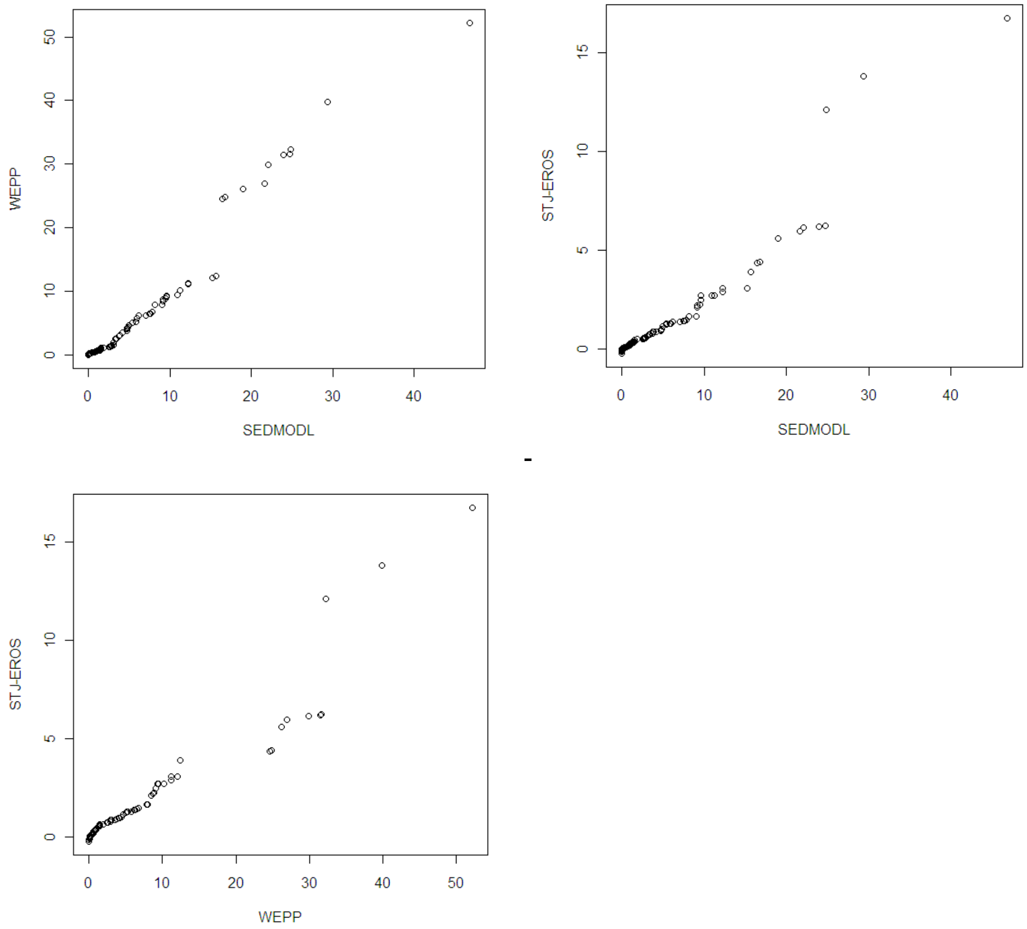

Figure 4.11. Q-Q Plots using log transformed sediment data (from left to right: SEDMODL vs. STJEROS; WEPP vs. STJEROS; SEDMODL vs. WEPP)

The statistical comparison between model outputs (table 4.5) indicated no significant difference between SEDMODL and WEPP: Road; but differences between other model pairings were significant.

Table 4.5. Summary of p-values for pairwise comparison of sediment data.

Pairwise comparison of slope	p-value (alpha = 0.017)
SEDMODL vs. WEPP: Road	0.31
SEDMODL vs. STJ-EROS	< 2.2e-16
WEPP: Road vs. STJ-EROS	4.6e-07

Figure 4.12 compares the outputs of all three models, illustrating the differences between each model output. WEPP: Road predicts road segment 16 to have the greatest sediment yield within the watershed. Alternatively, SEDMODL and STJ-EROS predict segment 87 to produce the greatest amount of sediment. SEDMODL and STJ-EROS predict similar trends among road segments, however they estimate different quantities of sediment; in general, SEDMODL estimates over two times as much sediment per segment as does STJ-EROS.

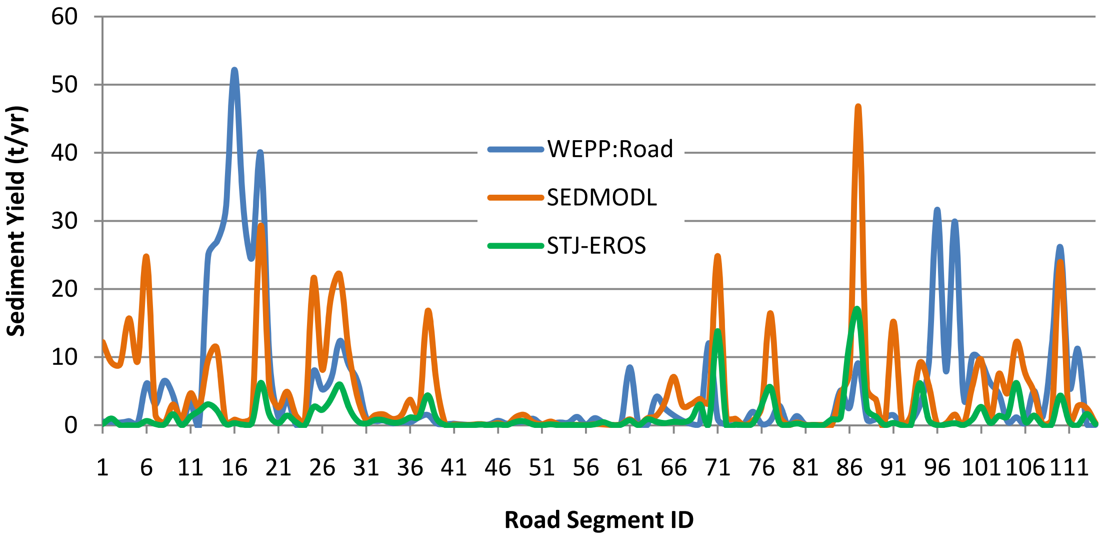

Figure 4.12. Comparison of total sediment yield (t/yr) for WEPP, SEDMODL, and STJ-EROS.

Figures 4.13- 4.15 show the relationship between sediment yields from each model pair. The trend lines and corresponding R^2 correlation coefficients were calculated for each paired comparison to evaluate whether a correlation exists between model outputs. There does not appear to be any relationship between the yields of SEDMODL and WEPP: Road (figure 4.13) or between WEPP: Road and STJ-EROS (figure 4.14); the R^2 values for both relationships are close to zero indicating no correlation between sediment estimations. An R^2 value of 0.57 for the relationship between SEDMODL and STJ-EROS indicate that there is a slight correlation between output.

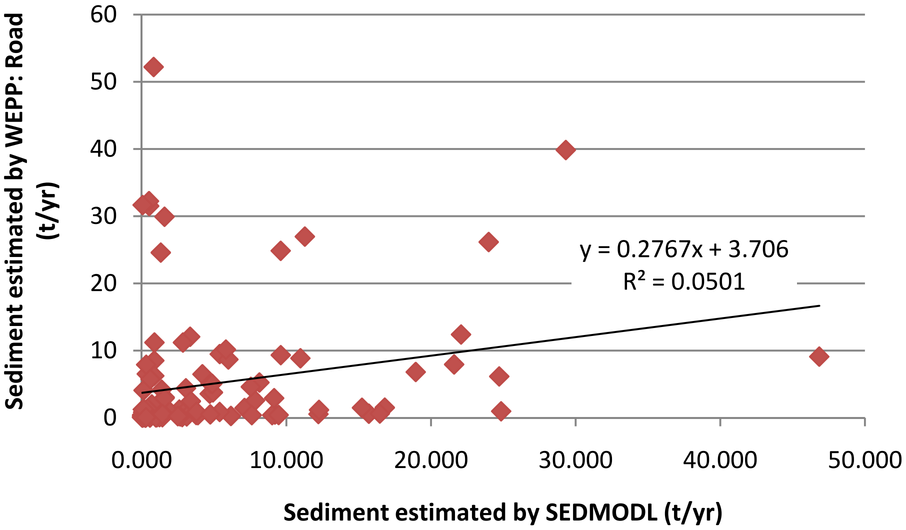

Figure 4.13. Scatter plot comparing sediment yields (t/yr) of SEDMODL and WEPP: Road.

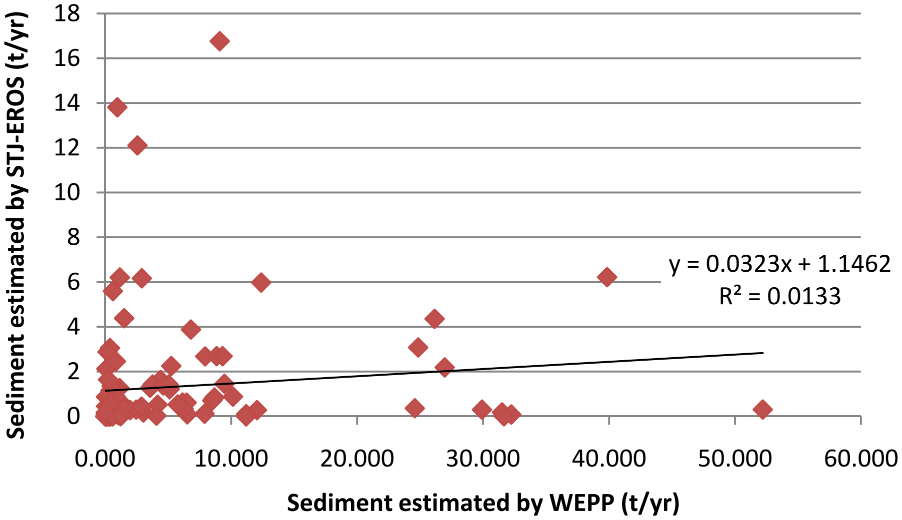

Figure 4.14. Comparison of sediment yield (t/yr) of WEPP: Road and STJ-EROS.

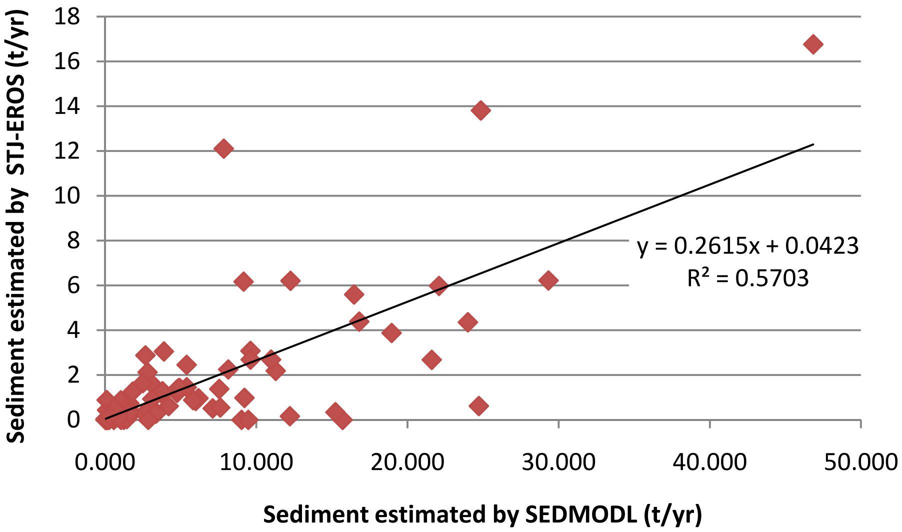

Figure 4.15. Comparison of sediment yield (t/yr) of SEDMODL and STJ-EROS.

To verify the results of the models, the road segments identified by the models to have high erosion and delivery potential were compared to those chosen through field classification. Through this comparison, the erosion prediction models were evaluated as to whether they can be effectively applied to the Corrego Horizonte watershed.

4.6 Comparison of model and field rankings

4.6.1 Sediment production potential

The classification system for field ranking of road segments uses a 1 – 5 score to describe the severity of erosion potential; five represents very high erosion potential and one represents low erosion potential. Scores were first assigned to each road segment according to field observations. Figure 4.16 illustrates the road segments within the Corrego Horizonte watershed and their score. A total of nine road segments received a score of 5, eight segments received a score of 4, twenty segments received a score of 3, sixteen segments received a score of 2, and sixty-one segments received a score of 1.

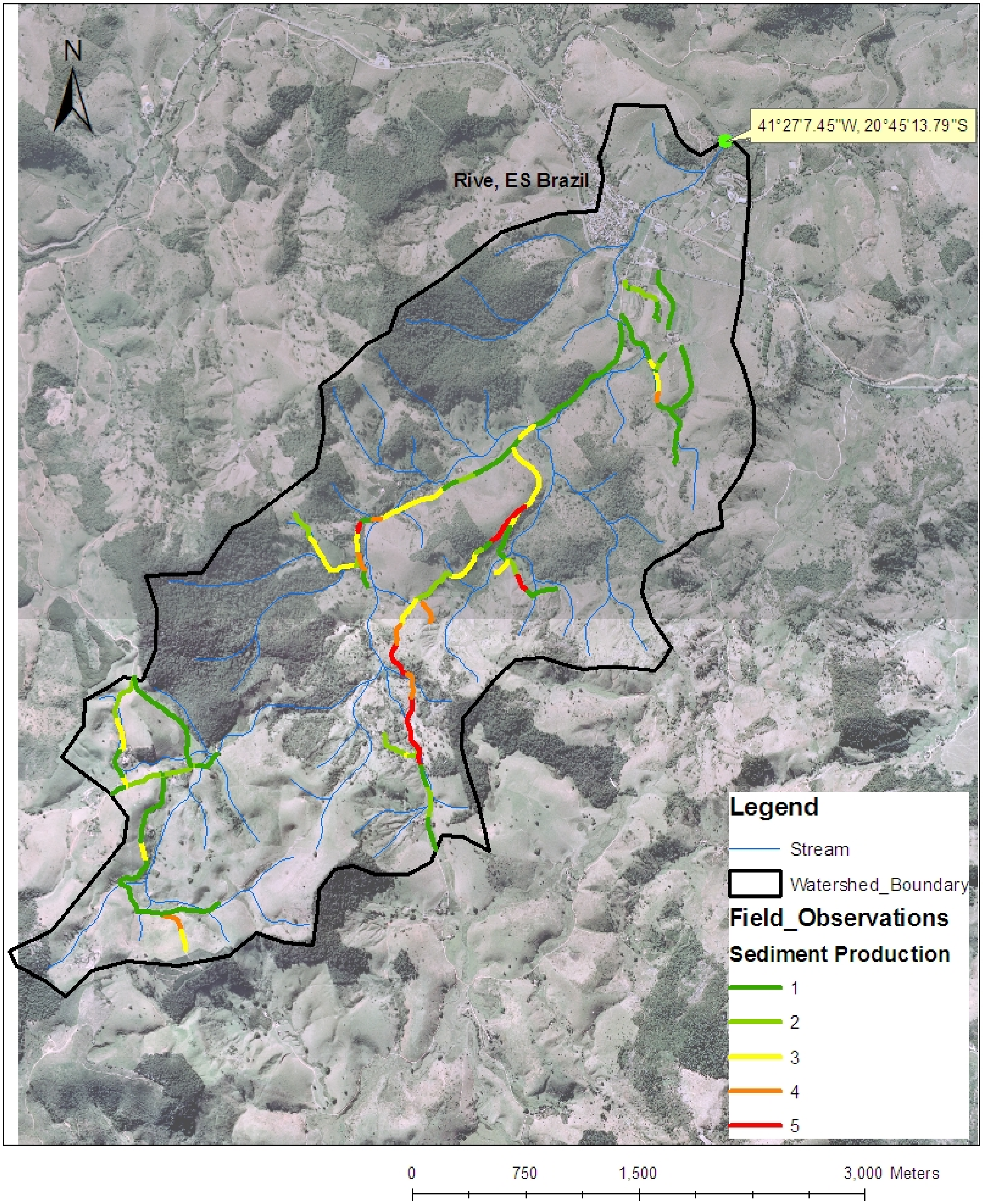

Figure 4.16. Road segments in the Corrego Horizonte watershed scored for sediment production using field observations. Scores 1-5 represent low to very high priority in terms of erosion potential.

To assign scores to each road segment evaluated by the models, roads were ranked from highest to lowest sediment yield (figures 4.17 – 4.19). The road segments were then divided into five groups according to the count of segments in each of the 5 ranked classes; the count of segments in each class was dictated by the number of segments assigned to that score based on field observations. For example, the nine road segments estimated as having highest sediment production were given a score of 5. Table 4.6 lists the road segments assigned to each score according by each method of evaluation.

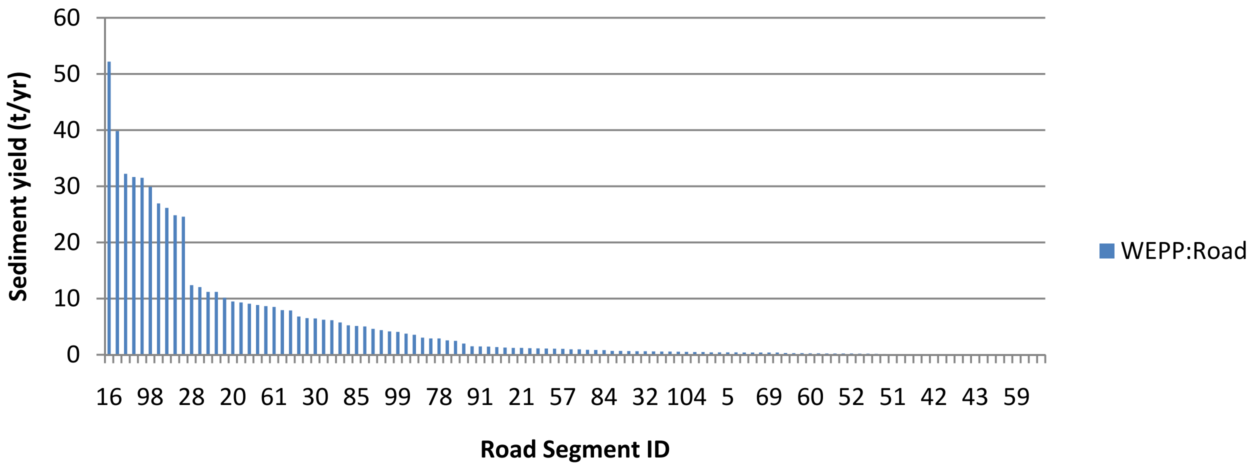

Figure 4.17. Rankings of road segments with highest sediment yield to lowest sediment yield (t/yr) as estimated by WEPP: Road.

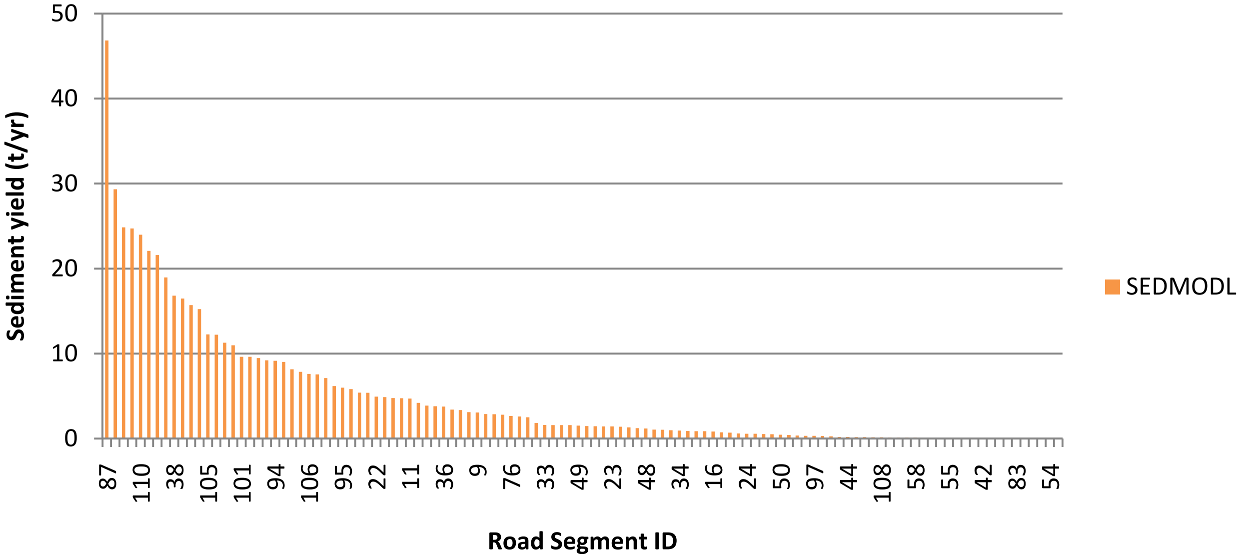

Figure 4.18. Rankings of road segments with highest sediment yield to lowest sediment yield (t/yr) as estimated by SEDMODL.

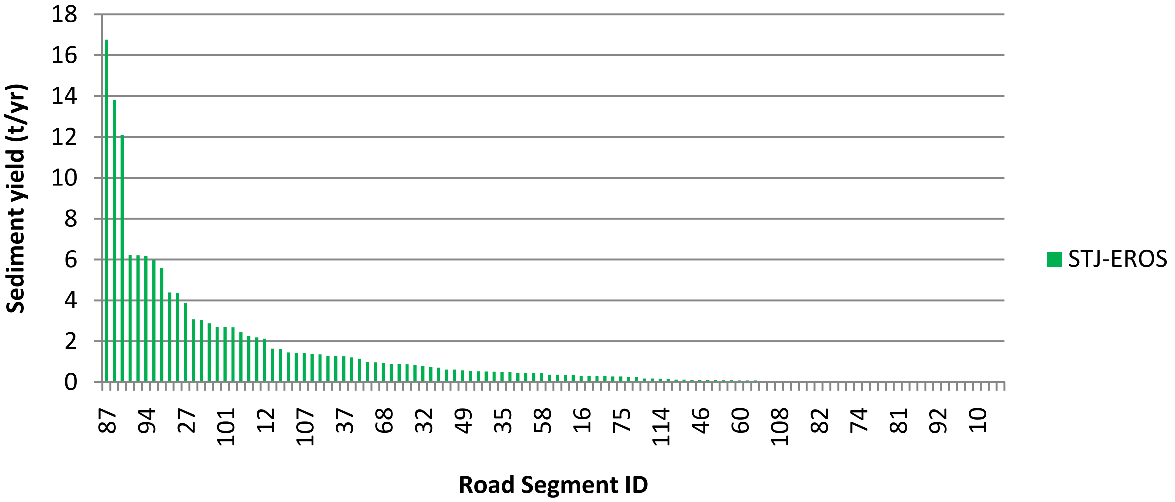

Figure 4.19. Rankings of road segments with highest sediment yield to lowest sediment yield (t/yr) as estimated by STJ-EROS.

Table 4.6. List of road segments and their assigned final classification score (5-1) according to evaluation method.

Score	Road Segments: Field Observation	Road Segments: SEDMODL	Road Segments: WEPP: Road	Road Segments: STJ-EROS
5	15, 19, 29, 94, 95, 98, 101, 103, 110	87, 19, 71, 6, 110, 28, 25, 27, 38	16, 19, 17, 96, 15, 98, 14, 110, 13	87, 71, 86, 19, 105, 94, 28, 77, 38
4	61, 84, 89, 93, 99, 100, 104, 109	77, 4, 91, 105, 1, 14, 29, 101	18, 28, 70, 109, 112, 100, 20, 101	110, 27, 13, 69, 76, 29, 101, 25
3	8, 9, 11, 13, 14, 16, 18, 23, 25, 31, 27, 38, 69, 76, 77, 86, 87, 91, 92, 111	14, 5, 2, 94, 3, 26, 86, 106, 103, 66, 39, 95, 100, 20, 88, 2, 107, 85, 104, 11	87, 29, 95, 61, 25, 97, 27, 8, 30, 102, 6, 111, 26, 85, 107, 103, 9, 64, 99, 22	88, 26, 14, 12, 113, 9, 20, 22, 107, 103, 104, 89, 11, 37, 85, 36, 2, 39, 68, 84
2	17, 20, 22, 24, 28, 46, 58, 60, 71, 75, 78, 85, 88, 97, 105, 107	30, 69, 89, 36, 65, 70, 68, 9, 67, 112, 12, 76, 21, 113, 27, 33	11, 7, 94, 78, 86, 65, 75, 38, 91, 66, 80, 108, 55, 21, 105, 37	100, 63, 95, 32, 33, 61, 6, 30, 49, 106, 111, 64, 66, 35, 48, 23
1	1, 2, 3, 4, 5, 6, 7, 10, 12, 21, 26, 27, 30, 32, 33, 34, 35, 36, 39, 40, 41, 41, 42, 43, 44, 45, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 59, 62, 63, 64, 65, 66, 67, 68, 70, 72, 73, 74, 79, 80, 81, 82, 83, 90, 96, 102, 106, 108, 112, 113, 114	7, 78, 98, 49, 32, 35, 93, 23, 64, 18, 72, 48, 10, 63, 73, 34, 109, 61, 102, 16, 31, 75, 111, 24, 52, 15, 17, 50, 80, 8, 46, 97, 114, 92, 90, 44, 57, 51, 60, 108, 40, 41, 99, 58, 84, 79, 43, 55, 95, 81, 82, 42, 45, 62, 53, 83, 74, 47, 59, 54, 56	31, 90, 57, 71, 50, 89, 88, 84, 67, 33, 56, 77, 32, 4, 49, 93, 1, 104, 2, 35, 36, 53, 5, 48, 58, 106, 3, 69, 54, 10, 34, 39, 60, 47, 41, 113, 74, 52, 68, 76, 40, 45, 51, 44, 56, 12, 62, 42, 72, 81, 23, 63, 43, 79, 82, 73, 114, 59, 83, 24, 92	67, 78, 58, 34, 18, 102, 91, 16, 21, 65, 98, 70, 75, 80, 31, 15, 7, 114, 1, 52, 57, 97, 46, 109, 44, 8, 50, 60, 17, 73, 90, 79, 108, 54, 93, 99, 40, 82, 59, 45, 47, 42, 74, 62, 55, 43, 96, 81, 53, 56, 83, 41, 92, 51, 24, 72, 112, 10, 5, 3, 4

By calculating the difference between the score assigned by field observations and the score assigned by each model, the models were assessed as to their ability to identify roads with high erosion potential. For road segments successfully ranked by the model, the difference between scores would be 0. For road segments unsuccessfully ranked by the model, the difference between scores would be 4.

Theoretically, the more matches between model and field rankings, the better the ability of the model to predict erosion potential within the Corrego Horizonte watershed.

Tables 4.7 – 4.9 present the number of road segments with different scores from field observations. The majority of road segments received scores of 2 and 1 which in this case are considered the least priority in regards to erosion potential and management; the comparison therefore focuses on the ability of models to rank road segments with higher erosion potential (scores 3 – 5). The WEPP: Road model has the highest number of road segments that match field observation rankings for classifications of 5, 4 and 3.

Table 4.7. The number of road segments with differences between SEDMODL and field rankings with scores of 5, 4, and 3.

SEDMODL			
	Field Score		
	5	**4**	**3**
Difference in rankings	Number of road segments		
0	2	0	3
1	0	5	7
2	3	1	10
3	2	2	0
4	2	0	0

Table 4.8. The number of road segments with differences between WEPP: Road and field rankings with scores of 5, 4, and 3.

WEPP: Road			
	Field Score		
	5	**4**	**3**
Difference in rankings	Number of road segments		
0	4	2	5
1	0	2	6
2	3	2	9
3	1	2	0
4	1	0	0

Table 4.9. The number of road segments with differences between STJ-EROS and field rankings with scores of 5, 4, and 3.

STJ-EROS			
	Field Score		
	5	**4**	**3**
Difference in rankings	Number of road segments		
0	2	0	4
1	0	7	8
2	4	0	8
3	3	1	0
4	0	0	0

Figure 4.20 visually illustrates which prediction models had the greatest percentage of road segments with scores that matched field rankings. For scores of 3, 4, and 5, WEPP: Road had the greatest percentage of matching road segments. Besides evaluating the number of road segments with matching rankings, however, the relative accuracy of these models can also be assessed by evaluating the number of road segments with a difference of 4 between scores; a great percentage of mismatched road segments could indicate the inability of a model to identify roads with high erosion potential. Figure 4.21 illustrates the percentage of roads segments ranked by each model to have a difference of 4 between scores. SEDMODL has the highest percentage of mismatched road segments when compared to field observations. STJ-EROS had no road segments that had a difference of 4 between scores.

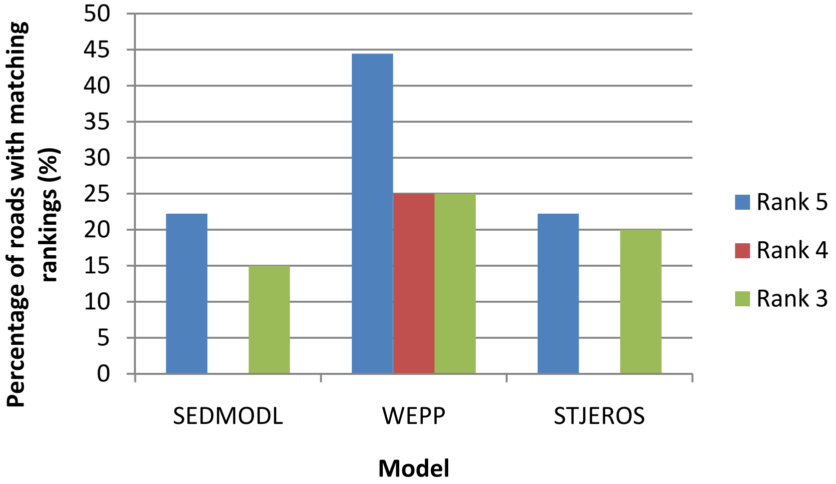

Figure 4.20. The percentage of road segments with matching rankings for classifications of 5, 4, and 3.

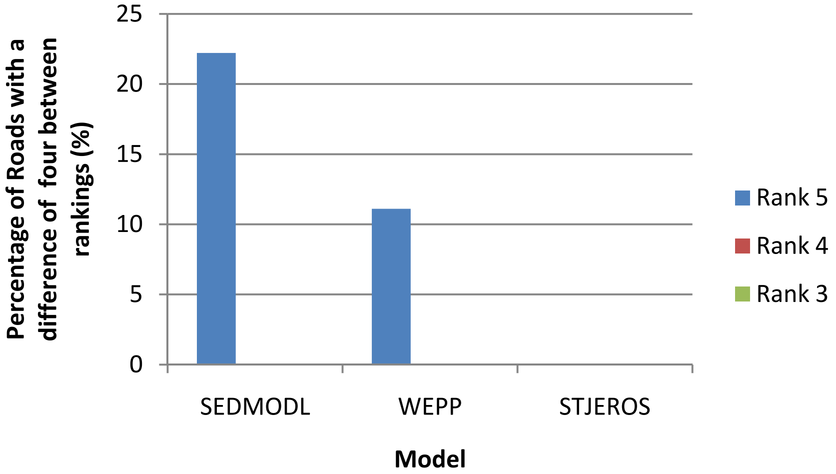

Figure 4.21. The percentage of road segments with a difference of four between rankings for classifications of 5, 4, and 3.

Simply looking at the difference between rankings from field observations and model estimations, it appears WEPP: Road does the best job of all three models at predicting roads with high erosion potential. This being said however, the percentage of road segments matching field observations is less than 50%. Of all three top scores, only approximately 1/3 of the road segments match field observations. This brings into question the ability of WEPP: Road to identify roads with the potential for high sediment production.

In addition to comparing model predictions to field observations, model predictions were compared to one another. A Spearman's rank test was run to determine if there was a correlation between the way models ranked the road segments. Each road segment was ranked from 1 to 114, representing highest sediment yield and lowest sediment yield respectively. Spearman's rank test is a nonparametric test for evaluating the relationship between two variables by calculating a correlation coefficient. Table 4.10 summarizes the values of the correlation coefficient, rho, for each test. Rho can range from 0 to ±1; values close to 0 represent little to no correlation between variables. As indicated by table 4.10, there are no correlations between model rankings.

Table 4.10. Summary of Spearman correlation coefficients between model rankings.

Model Comparisons	Spearman's rho
SEDMODL vs. WEPP: Road	-0.061
SEDMODL vs. STJ-EROS	0.031
WEPP: Road vs. STJ-EROS	0.007

As indicated by the various statistical tests and analytical observations, there are few similarities between models as well as between model results and between field observations. It appears that each model operates under a different set of assumptions to produce varying results. Each model evaluated the road network differently, placing varying degrees of importance on different inputs. To better understand why certain roads were estimated to have high sediment yields by the models, comparisons were made in length, slope, and width. It is assumed that the longer and wider the road and the steeper the slope, the more potential for sediment production. Approximately 82% of the roads scored as 5's and 4's for erosion potential by SEDMODL have road lengths greater than 100 m; 41% of the roads had slopes greater than 10%. Similarly in WEPP:

Road, approximately 88% of the road segments scored as 5's and 4's had road lengths greater than 100 m and 18% had slopes greater than 10%. With STJ-EROS, approximately 71% of the roads had lengths greater than 100 m and 53% had slopes greater than 10%. For both SEDMODL and STJ-EROS, approximately 78% of the roads scored as a 5 had a road width of greater than 4.5 m, whereas only 44% of WEPP: Road segments had widths greater than 4.5 m. These simple observations verify the assumptions made by the models that road length and road slope have a significant effect on erosion potential.

4.6.2 Sediment delivery potential

Although the model outputs could not be scored according to sediment delivery potential, the classification system was used to score the roads based on field observations. The majority of roads within the Corrego Horizonte watershed are far from the stream. For those segments that are nearby the stream, the fill-slopes are sufficiently vegetated so as to slow down runoff and deposit sediment. Figure 4.22 illustrates the road segments and their corresponding scores for sediment delivery potential assigned by field observation. A total of four roads were given scores of 5, representing a very high potential for sediment delivery from the road segment. Three of these four road segments received scores of 5, 4, and 3 for sediment production potential. Figure 4.23 depicts the one road segment which received a score of 5 for both sediment delivery and sediment production. It is 55 m long with a slope of 19% and is within 10 m of the stream and has little to no vegetation to slow down runoff velocity and reduce runoff volume.

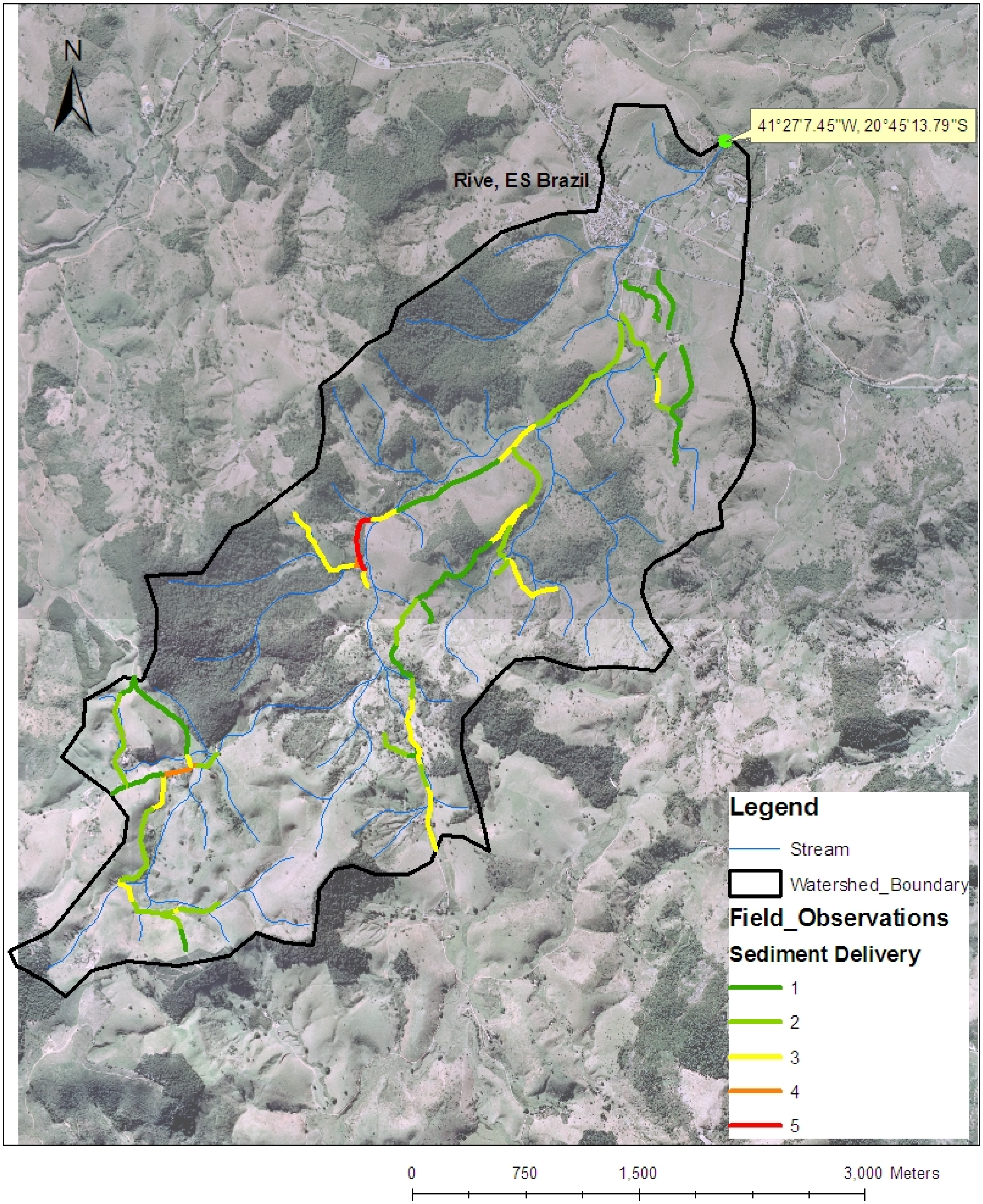

Figure 4.22. Road segments in the Corrego Horizonte watershed scored according to sediment delivery potential based on field observations. Scores 1 - 5 represent low to very high potential for delivery of sediment to streams.

Figure 4.23. Photos of road segment 94 which received scores of 5 for both sediment production and sediment delivery using the field classification system.

A total of two segments were given scores of 4 for sediment delivery potential, twenty-six segments received a score of 3, thirty-eight segments received a score of 2, and forty-four segments received a score of 1. Generally, the fill-slopes in the Corrego Horizonte watershed have 75-100% vegetative cover and moderate slopes. Figure 4.24 depicts a fill-slope that would most likely slow runoff velocity and reduce runoff volume enough so that sediment would be deposited before the stream.

Figure 4.24. Example of fill-slope with good vegetative cover that would generally trap the majority of sediment traveling off of a road segment.

The classification system for sediment production and sediment delivery can be a useful tool for making management decisions both in terms of road infrastructure and environmental protection. Sediment production potential alone cannot accurately identify road segments that may be contributing to environmental degradation. Not only is it important to a source of sediment, but also its transport pathway.

4.7 Sensitivity analysis

A sensitivity analysis was completed on each model to identify the relative sensitivity of each input on the estimation of total sediment yield. Since each model predicted sediment production differently, a sensitivity analysis can give insight as to what parameters receive the greatest importance in the calculation of sediment yield. In addition, a sensitivity analysis helps to identify which factors should be most carefully measured if the desired output is to be as accurate as possible.

4.7.1 WEPP: Road

WEPP: Road utilizes multiple equations to determine runoff and sediment load from each road segment, fill-slope, and buffer. A variety of scenarios were simulated to evaluate how different road conditions affect sediment loading. In each scenario, two inputs were varied to calculate change in sediment yield. The results were graphed to illustrate the relative effect of each variable on the other.

WEPP: Road is the only model being evaluated which does not ask the user to calculate sediment output using a given equation. Instead, the user inputs each factor through the user interface provided on the internet and receives a summary of sediment output for each road segment. Since the equations used in the calculation of sediment yield are not visible, it is less obvious how each factor affects total sediment output (kg/yr). Since multiple equations are used to calculate runoff and erosion, the relationships between each factor are more complex. Shown in figure 4.25 is the influence of road type on sediment output (kg/yr) from the road segment as slope increases. Outsloped rutted roads and insloped bare ditch roads have very similar effects on sediment yield. This correlates with the suggestion by WEPP: Road that insloped bare ditch roads with ruts be reclassified as outsloped rutted. Segments characterized as outsloped unrutted and insloped vegetated ditch generally generate less sediment since they are characterized by more stable road surfaces or vegetated ditches to slow and trap sediment. Figure 4.26 illustrates the influence of road type on sediment output (kg/yr) from the fill-slope and buffer, as slope increases. The trends are generally the same, however the magnitude of sediment yield decreases significantly due to deposition along the fill-slope and buffer.

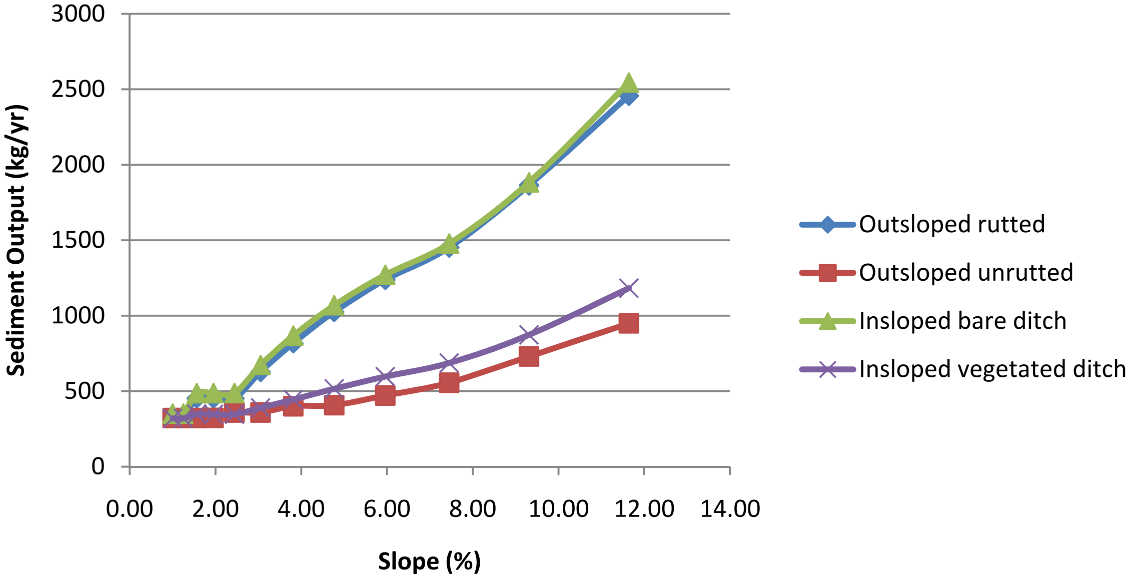

Figure 4.25. The effect of road type on sediment output (kg/yr) from the road segment as slope (%) increases using WEPP: Road. Baseline conditions include native road with high traffic intensity, road length 50 m, road width 4.5 m, fill length 20 m, fill slope1%, buffer length 20 m, buffer slope 0.5%, and 0% rock fragments.

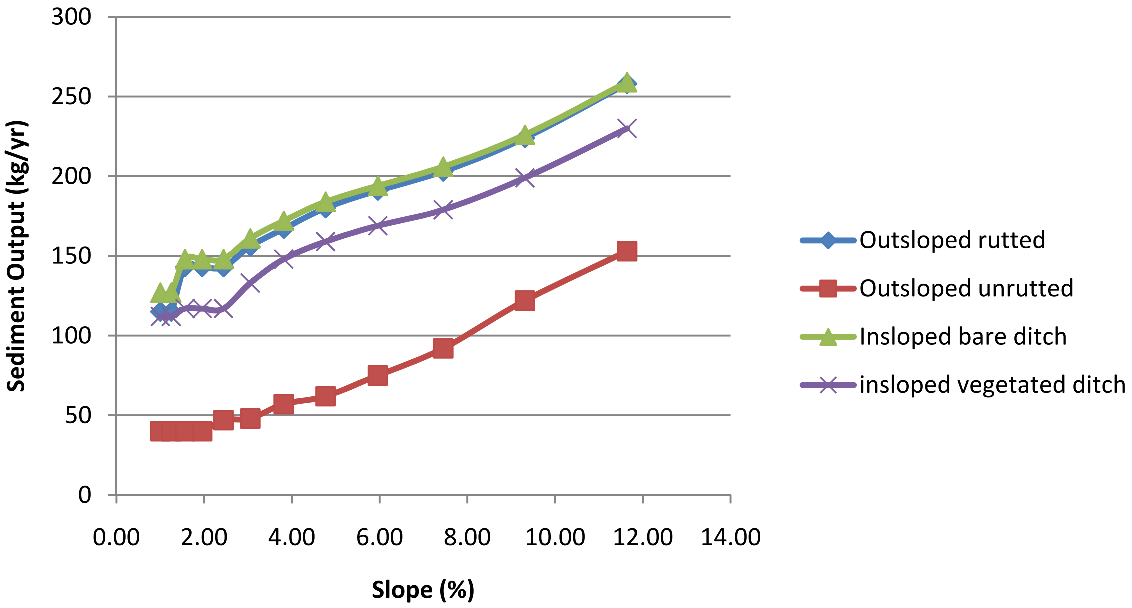

Figure 4.26. The effect of road type on sediment output (kg/yr) from the fill-slope and buffer as slope (%) increases using WEPP: Road. Baseline conditions include native road with high traffic intensity, road length 50 m, road width 4.5 m, fill length 20 m, fill-slope1%, buffer length 20 m, buffer slope 0.5%, and 0% rock fragments.

Both road length and slope significantly affect sediment yield for the road segment (figure 4.27). As illustrated by the graph, sediment yield increases at a greater rate for longer road lengths. Sediment yield for a road length of 150 m increases at a rate of approximately 1324 kg/yr/% slope which is almost seven times that of the rate of increase for a road length of 50 m, which is 191 kg/yr/% slope.

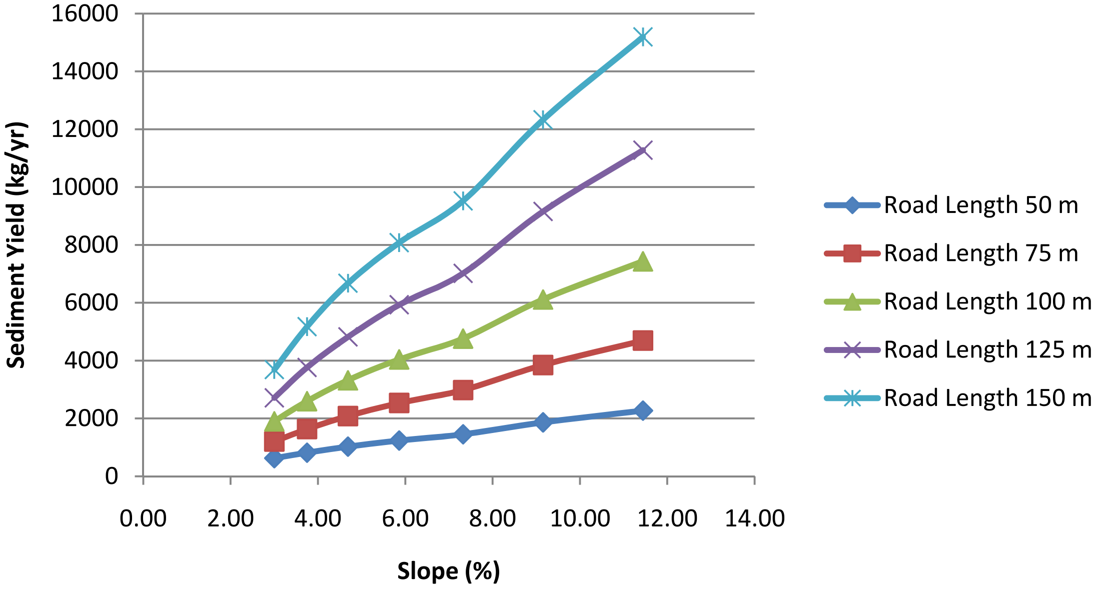

Figure 4.27. The effect of road length (m) on sediment output (kg/yr) from the road as slope (%) increases using WEPP: Road. Baseline conditions include: native, outsloped rutted road with high traffic intensity, road width 4.5 m, fill-slope 0.1%, fill-length 50 m, buffer slope 0.1%, buffer length 50 m, and 0% rock fragments.

The fill-slope and buffer affect the amount of sediment that is deposited versus what is delivered to a nearby stream. Figure 4.28 illustrates the influence of fill-slope length on sediment yield as buffer length increases. This demonstrates the relationship between the effectiveness of a fill-slope versus a buffer. The difference in sediment reduction is less pronounced between fill-slope lengths as compared to buffer lengths. There is a significant reduction in sediment as the buffer length increases to 50 m; after this point, sediment yield stabilizes around 50 kg/yr. Conversely, figure 4.29 shows the effect of buffer length on sediment yield from the buffer as fill-slope length increases. In this case, there is a greater difference in sediment yield as buffer length changes from 0.3 m to 20 m; there is a less pronounced difference in sediment reduction as fill-slope length increases. Therefore, it is concluded that buffer length is a more significant input than fill-slope length. This could be due to the assumption that the buffer is characteristic of a 20-yr forest whereas the fill-slope is assumed to have 50% vegetative cover. This corresponds to the results of the sensitivity analysis completed by Rhee et al. 2004. Their study determined that buffer topography and geometry significantly influence sediment delivery; they suggest dividing the road network based on buffer characteristics instead of road topography (Rhee et al., 2004).

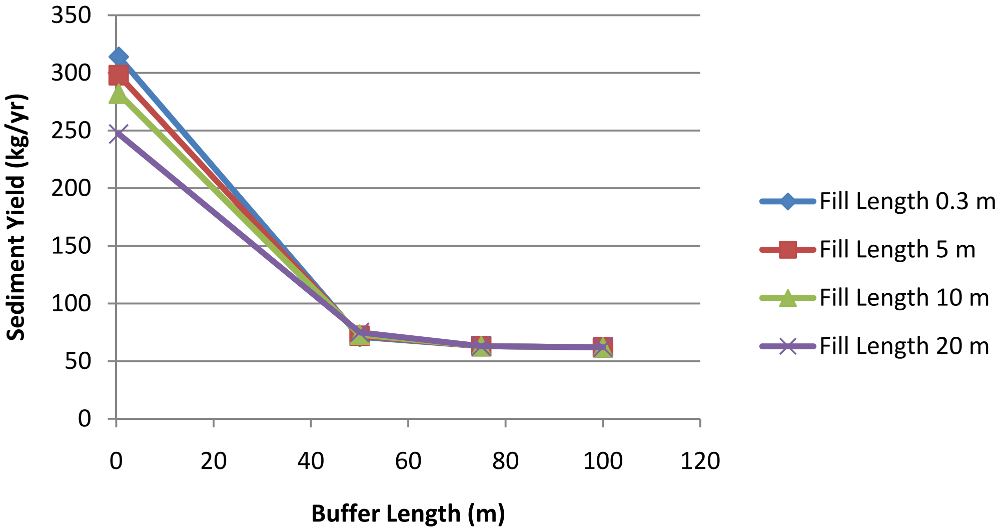

Figure 4.28. The effect of fill-slope length (m) on sediment yield (kg/yr) from the buffer as buffer length (m) increases using WEPP: Road. Baseline conditions include: native, outsloped rutted road with high traffic intensity, road slope 1%, road length 50 m, road width 4.5 m, fill-slope 1%, buffer slope 1%, and 0% rock fragments.

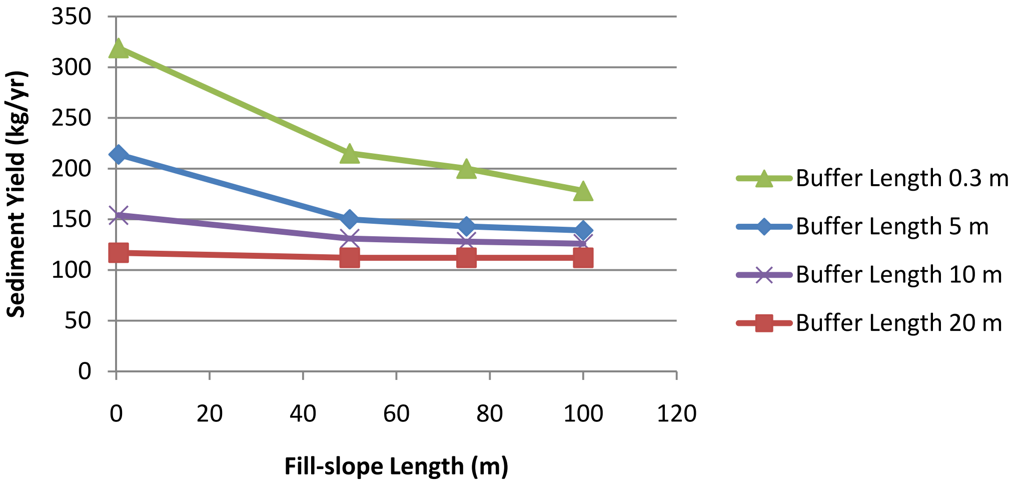

Figure 4.29. The effect of buffer length (m) on sediment yield (kg/yr) from the buffer as fill-slope length (m) increases using WEPP: Road. Baseline conditions include: native, outsloped rutted road with high traffic intensity, road slope 1%, road length 50 m, road width 4.5 m, fill-slope 1%, buffer slope 1%, and 0% rock fragments.

The influence of the slope of a buffer on sediment yield as the buffer length increases is illustrated by figure 4.30. The general trend shows an increase in sediment yield around 75 to 100 m of the buffer length depending on the slope. This is followed by a sharp decrease in sediment for approximately 50 m, followed by a gradual increase in sediment at the end of the buffer. Appendix C provides additional detail regarding the effect of buffer slope and length on sediment yield as various factors are adjusted.

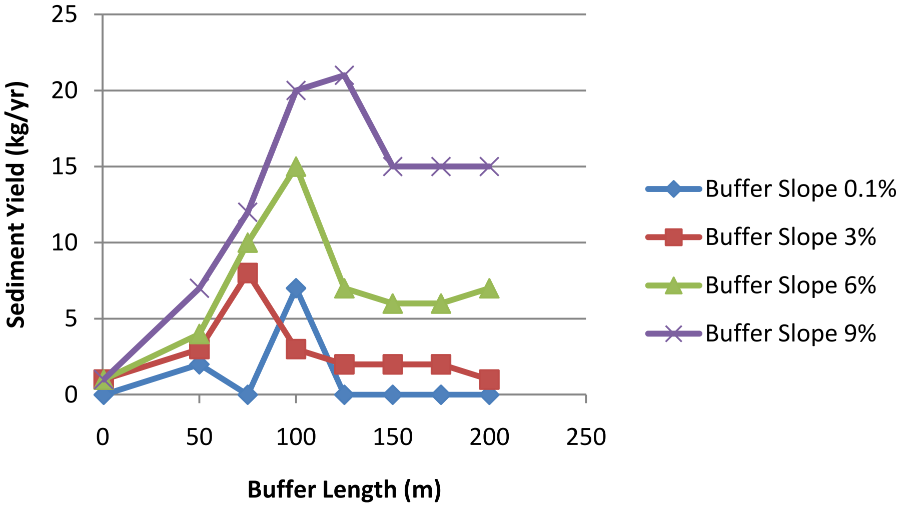

Figure 4.30. The effect of buffer slope (%) on sediment yield (kg/yr) from the buffer as buffer length (m) increases using WEPP: Road. Baseline conditions include: native, outsloped rutted road with high traffic intensity, road slope 1%, road length 50 m, road width 4.5 m, fill-slope 0.1%, fill length 50 m, and 0% rock fragments.

Soil type has the potential to greatly affect sediment yield as it is a main component of determining erodibility. Figures 4.31 and 4.32 illustrate the influence of soil type and road type on sediment yield from the road versus the buffer. In both cases, road segments with silt loam soils produce the greatest amount of sediment. In looking at the sediment produced by the road segment, sandy loam soils generally erode less than clay loam and loam soils. On the other hand, when looking at the amount of sediment leaving the buffer, the sediment yield from segments with loam soils is significantly less than that of silt loam. In this case, the fill-slope and buffer were characterized as 50 m with 0.1% slopes. An additional difference is that the buffers with sandy loam soils detain less sediment than those with clay loam soils. Road type does not have as great of an effect on the sediment yield from the road or the buffer; however, in the case of outsloped, unrutted roads, no sediment was found to leave the buffer.

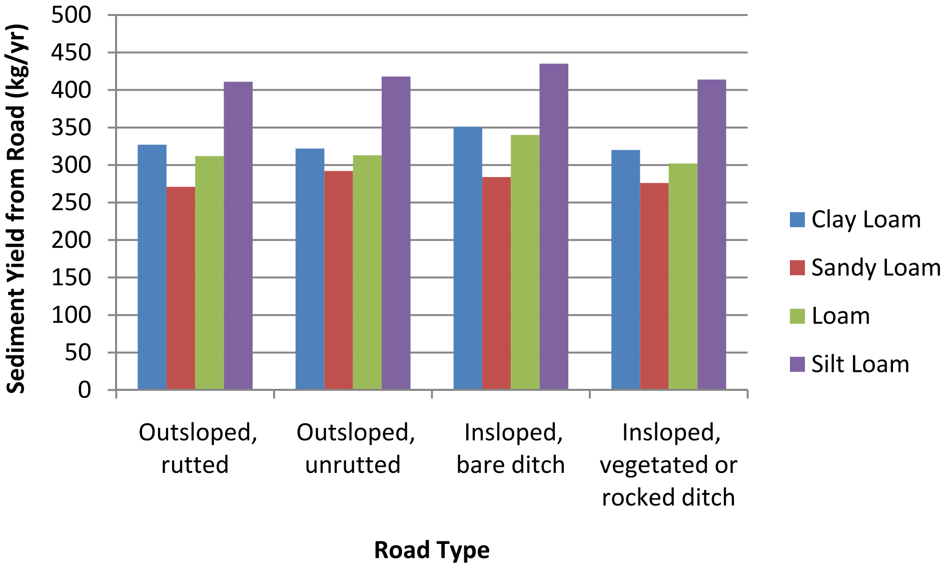

Figure 4.31. The effect of soil type and road type on sediment yield (kg/yr) from the road using WEPP: Road. Baseline conditions include: native road with high traffic intensity, road slope 1%, road length 50 m, road width 4.5 m, fill-slope 0.1%, fill length 50 m, buffer slope 0.1%, buffer length 50 m, and 0% rock fragments.

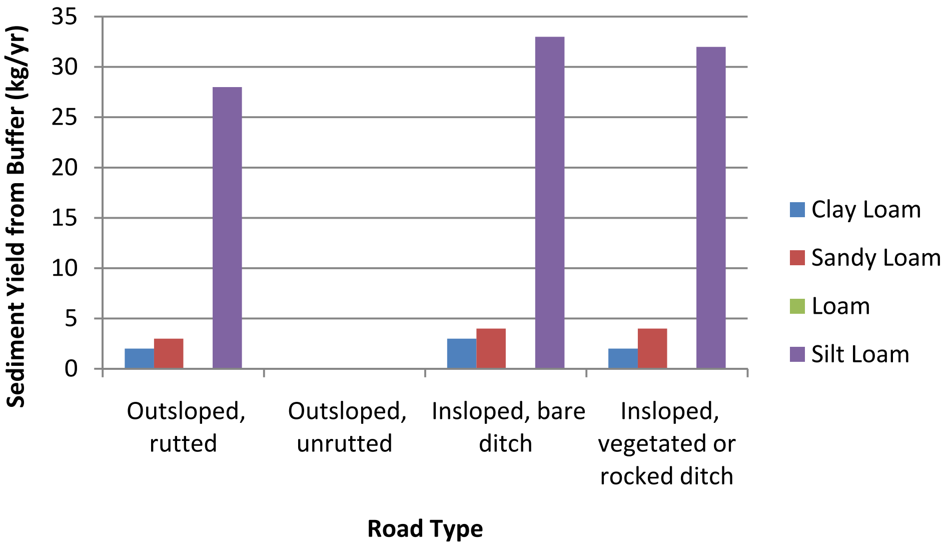

Figure 4.32. The effect of soil type and road type on sediment yield (kg/yr) from the buffer using WEPP: Road. Baseline conditions include: native road with high traffic intensity, road slope 1%, road length 50 m, road width 4.5 m, fill-slope 0.1%, fill length 50 m, buffer slope 0.1%, buffer length 50 m, and 0% rock fragments.

The effect of soil type and rock fragment on sediment yield is illustrated in figure 4.33. As the percentage of rock fragment increases, sediment yield increases. The relationships between soil types hold true from the previous figures: road segments with silt loam and clay loam soils produce more sediment than those with sandy loam or loam soils. This relationship changes as the percentage of rock fragments is 50% or greater. In this case, segments with loam, sandy loam, and clay loam soils generally produce similar sediment yields.

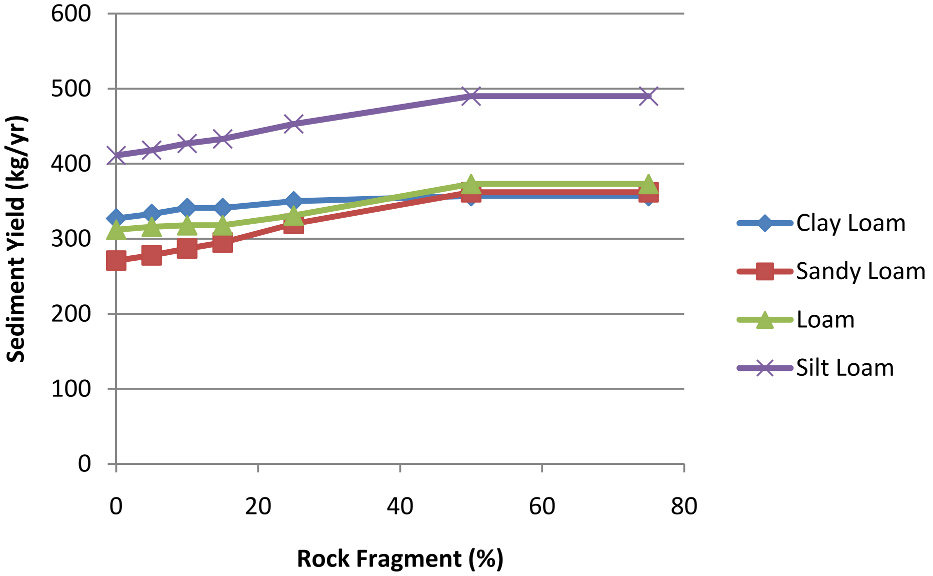

Figure 4.33. The effect of soil type and rock fragments (%) on sediment yield (kg/yr) from road segments using WEPP: Road. Baseline conditions include: native road with high traffic intensity, road slope 1%, road length 50 m, road width 4.5 m, fill-slope 0.1%, fill length 50 m, buffer slope 0.1%, and buffer length 50 m..

The climate file used in WEPP: Road as the basis for an adjusted climate also influences sediment yield estimation. The same parameters of mean maximum and minimum temperature, mean precipitation, average number of wet days, latitude, longitude, and elevation are applied to both base files. Figure 4.34 illustrates the difference in sediment yield estimation between using a Key West, Florida base file versus a Virgin Island (Dorothea Agricultural Experimental Station VI) base file. The baseline condition was an outsloping, rutted road with high traffic, a 1% slope, road dimensions of 50 m x 4.5 m, 0.1% fill-slope with length 50 m, 0.1% buffer slope with length 50 m and 0% rock fragments. Based on descriptions of the climate files, the following parameters are used from the base file: wind, solar radiation, dewpoint, and time-to-peak; there is no way to adjust these factors.

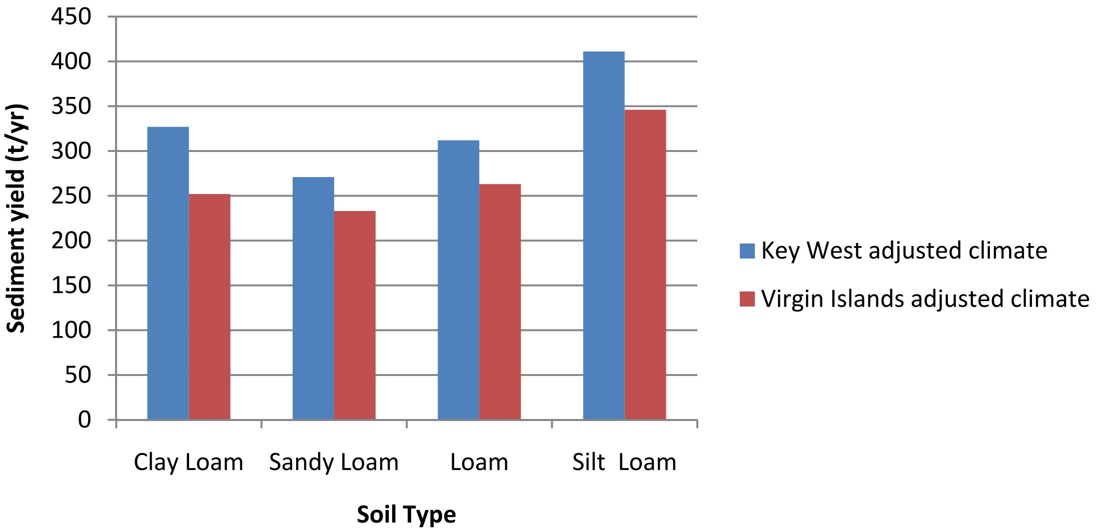

Figure 4.34. Effect of two different base climate files on sediment yield as estimated by WEPP: Road. Baseline conditions include: native, outsloping rutted road with high traffic intensity, road slope 1%, road length 50 m, road width 4.5 m, fill-slope 0.1%, fill length 50 m, buffer slope 0.1%, buffer length 50 m, and 0% rock fragments.

4.7.2 SEDMODL

SEDMODL utilizes one linear equation which multiplies a series of factors. As a result, it is relatively clear that an increase or decrease in a specific factor will increase or decrease sediment yield. The baseline condition used to evaluate each factor was determined based on the median values of each factor. This road segment was defined as a 119 m x 4.5 m spur road having a native surface with ruts, a slope of 5 – 10%, and a sediment delivery factor of 0.35. This road was created more than one year ago, has a cut-slope height of 7.5 m (gradient >60%) and cut-slope vegetative cover of 90%. For all the roads, the erosion rate and precipitation factor were constant at 0.0037 t/m^2 and 0.875, respectively.

Variables of significance in SEDMODL are slope, surface cover type, road type, cut-slope vegetative cover, and cut-slope height (figures 4.35-4.39). Each input of SEDMODL has a multiplicative effect on total sediment output. For those inputs associated with direct field measurements like road length or width, an increase by 10% will result in a 10% increase in sediment output. For the remaining variables, the sediment output increases or decreases by the magnitude of change. Those inputs with large ranges of magnitude are those that can have great influence. The ranges associated with each factor are not set up into equal intervals; the extreme case of each range is often significantly greater than the other conditions. For example, traffic intensity ranges from abandoned roads with a factor value of 0.1, to main haul and highway roads with factor values of 120. As shown in figure 4.35, the choice of traffic intensity can greatly affect the sediment output of a road segment. Similarly, slope and surface cover type can have significant effects depending on condition (figures 4.36 and 4.37). Cut-slope factors affect sediment output to a lesser extent. As shown in figures 4.38 and 4.39, sediment output changes by approximately 1 t/yr as vegetative cover of the cut-slope ranges from 0-100% and by 0.5 t/yr as cut-slope height varies from 1.5 to 7.5 m.

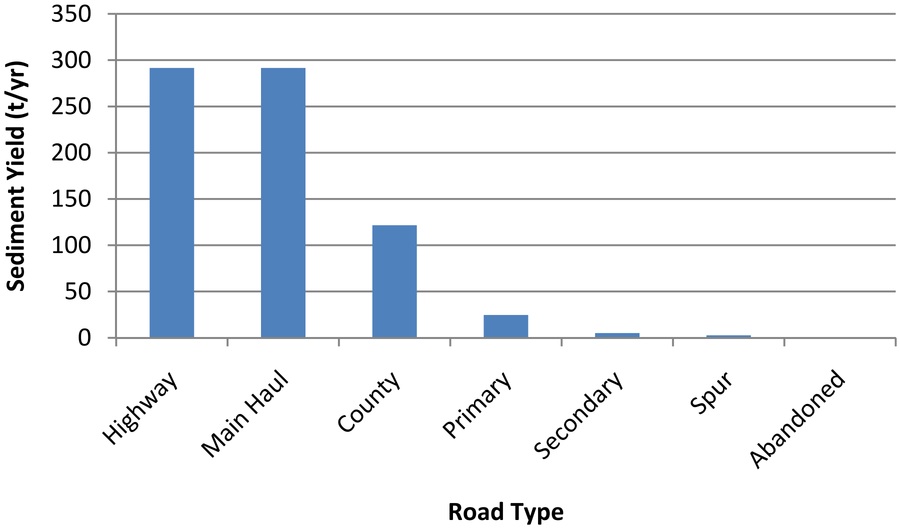

Figure 4.35. Effect of road type on sediment yield in SEDMODL with the following baseline conditions: native surface road with ruts, length of 119 m, width of 4.5 m, 5% slope, older than 2 yrs, 90% vegetated cut-slope with slope of >60%, and a sediment delivery ratio of 0.35.

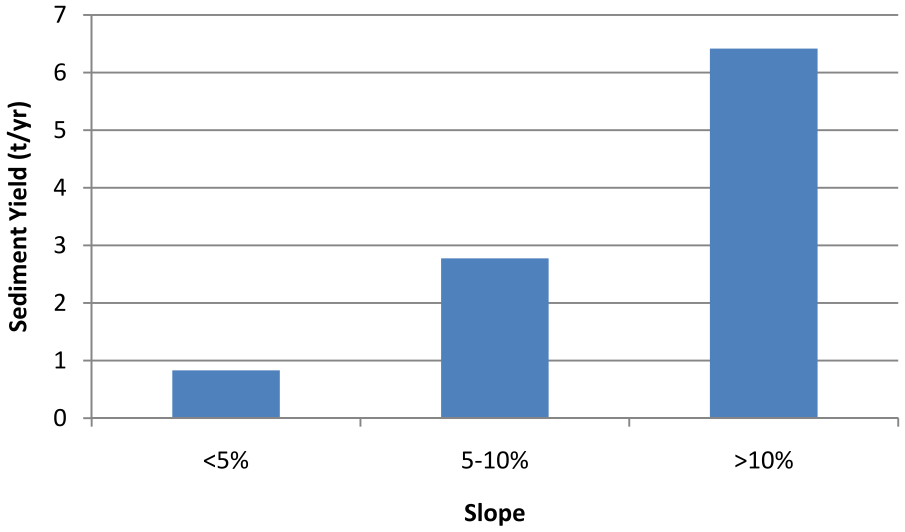

Figure 4.36. Effect of slope of a road segment on sediment yield in SEDMODL with the following baseline conditions: native surface spur road with ruts, length of 119 m, width of 4.5 m, older than 2 yrs, 90% vegetated cut-slope with slope of >60%, and a sediment delivery ratio of 0.35.

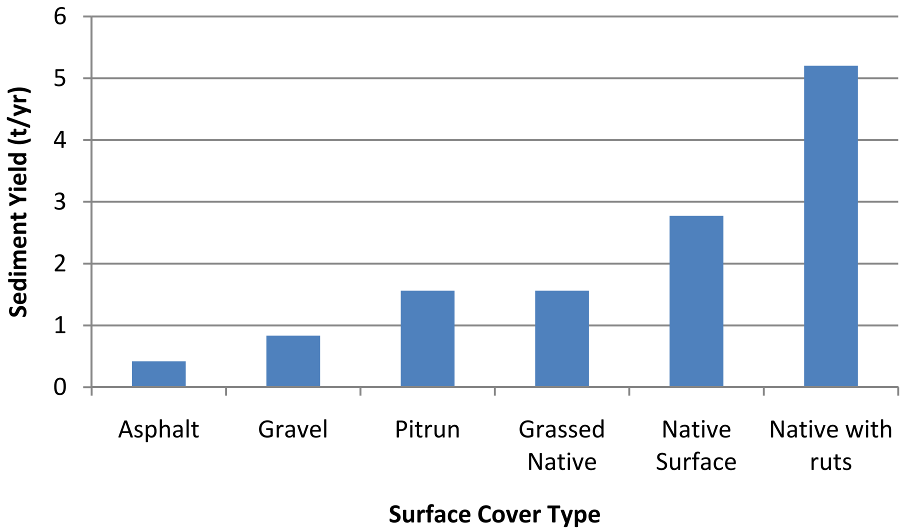

Figure 4.37. Effect of road surface type on sediment yield in SEDMODL with the following baseline conditions: spur road, length of 119 m, width of 4.5 m, 5% slope, older than 2 yrs, 90% vegetated cut-slope with slope of >60%, and a sediment delivery ratio of 0.35.

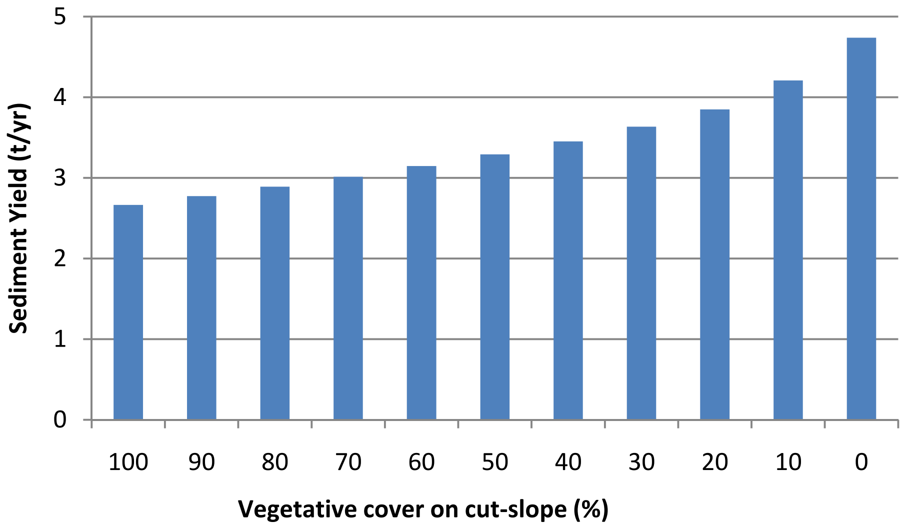

Figure 4.38. Effect of cut-slope vegetative cover on sediment yield in SEDMODL with the following baseline conditions: native surface spur road with ruts, length of 119 m, width of 4.5 m, 5% slope, older than 2 yrs, cut-slope gradient of >60%, and a sediment delivery ratio of 0.35.

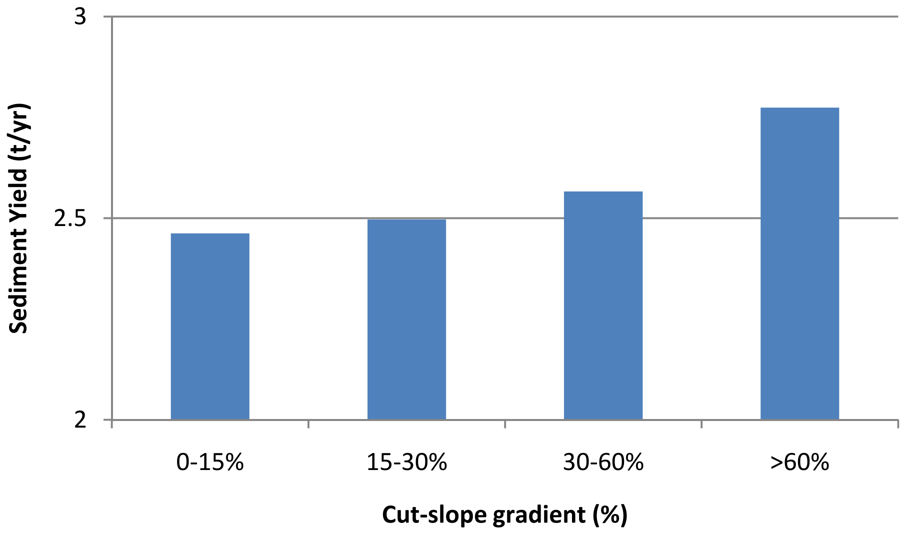

Figure 4.39. Effect of cut-slope gradient on sediment yield in SEDMODL with the following baseline conditions: native surface spur road with ruts, length of 119 m, width of 4.5 m, 5% slope, older than 2 yrs, 90% vegetated cut-slope, and a sediment delivery ratio of 0.35.

These results correlate with the findings presented in the literature review. In general, studies have shown that road characteristics such as slope, length, traffic intensity, and soil type affect sediment output more so than other factors (Luce and Black, 1999; Elliot et al., 1999a; Ebisemiju, 1990).

4.7.3 STJ-EROS

The input values for STJ-EROS were taken directly from field measurements and thus the sensitivity of each factor could be evaluated by varying each input by a specified percentage. The baseline scenario for STJ-EROS was determined based on the median values of each input. A baseline condition was an ungraded segment with dimensions 119 m x 4.5 m, a slope of 5.3%, and a sediment delivery ratio of 35%. Figures 4.38-4.40 illustrate the effect of slope, road length, and rainfall on sediment yield (kg/yr). As shown by figure 4.40, slope has a significant influence on sediment yield. This is evident by the equation since slope is raised to a power of 1.5. Slope does not seem to have a significant effect until it is greater than 10%, after which sediment yield increases significantly. Road length and width, as well as rainfall, have a linear relationship with total sediment yield (figures 4.41 and 4.42). As length or rainfall increase by 10%, sediment yield also increases by 10%. Again, the significance of the factors indicated by the sensitivity analysis agrees with those from previous studies. In general, slope is a good indicator of the degree of erosion; therefore it carries more weight than other road characteristics.

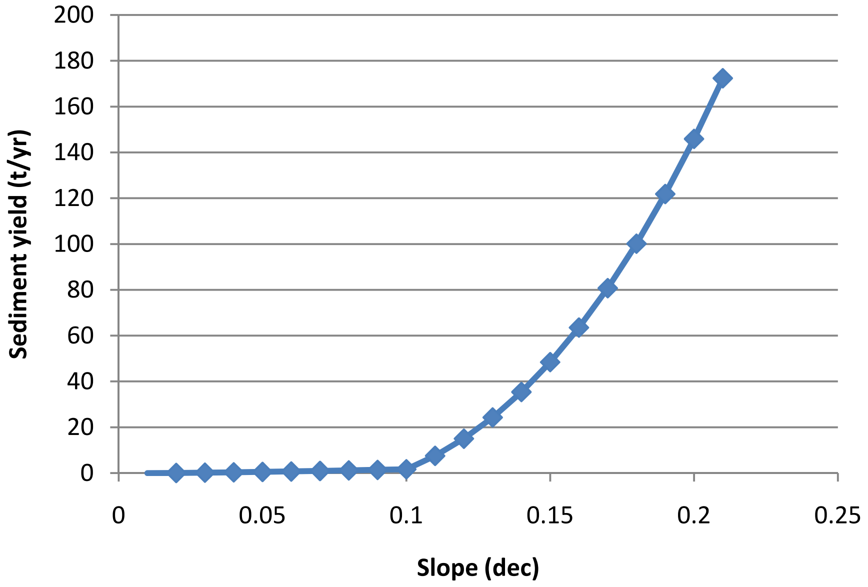

Figure 4.40. The effect of slope on sediment yield (t/yr) as estimated by STJ-EROS using the following baseline conditions: ungraded road, length 119 m, width 4.5 m, rainfall 129 cm, and sediment delivery ratio of 0.35.

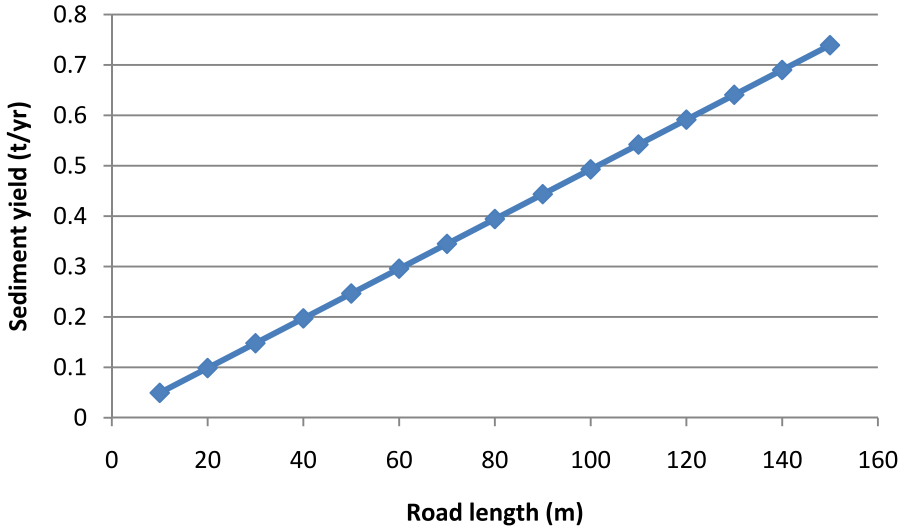

Figure 4.41. The effect of road length on sediment yield as estimated by STJ-EROS using the following baseline conditions: ungraded road, width 4.5 m, 5.3% slope, rainfall 129 cm, and sediment delivery ratio of 0.35.

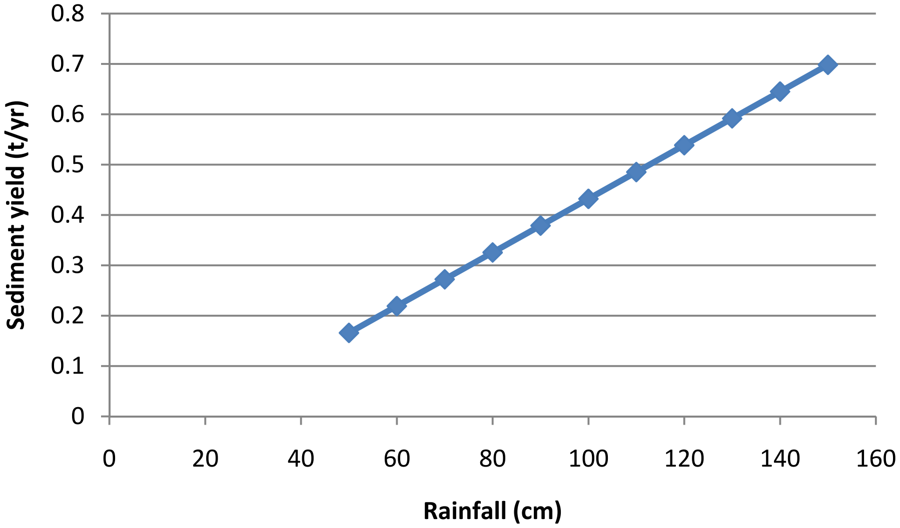

Figure 4.42. The effect of rainfall on sediment yield as estimated by STJ-EROS using the following baseline conditions: ungraded road, length 119 m, width 4.5 m, 5.3% slope, and sediment delivery ratio of 0.35.

Chapter 5. Conclusions and Recommendations

5.1 Model evaluation

The outputs of each model were compared not only quantitatively to determine differences in sediment yield estimation, but also qualitatively to determine differences in the process of road segment prioritization. Since no background data involving sediment yield is available, it is difficult to determine the accuracy of these models. This study does not seek to identify the ‘best’ or ‘worst’ model, but rather to assess the accuracy of results of each model by comparing them to first-hand field observations. Although accuracy is important in the selection of a model, it is equally important that a model used to assess erosion in tropical conditions be easy to use, have readily definable inputs, and make appropriate assumptions.

5.1.1 WEPP: Road

The WEPP: Road model is one of the few erosion prediction models available free online with a user-friendly interface. Since the WEPP model and its counterparts have been used extensively, there are many resources online to help the user in the measurement and description of inputs. These models were designed based mainly on forest conditions in the northwest United States and therefore make assumptions that may not apply to tropical conditions. The climate generator allows the user to adjust temperature, rainfall, the number of wet days, elevation, and geographic coordinates based on an existing climate file provided by the program; however, the adjusted climate still carries some attributes of original climate file. Depending on which base file is used for climate adjustment, the estimation of sediment yield can change.

In addition, the inputs of the WEPP: Road model can be confusing to interpret. Although a useful guide is provided for the user, many inputs change according to assumptions a user may make based on their specific site conditions. In the case of the Corrego Horizonte watershed, there are few roads with an existing buffer. For the segments that do have a buffer, it is inappropriate to assume that it is representative of a 20-yr old forest. WEPP: Road considers this an important attribute which can significantly affect the amount of sediment yield estimated; this assumption can negatively affect model accuracy in the tropics. In addition, soil types are limited and may not accurately represent the soils in tropical conditions. The sensitivity analysis indicates there may be a significant difference in sediment estimation based on the soil type chosen. It is not clear how factors affect one another and what may be appropriate in varying scenarios (i.e in the example of buffer topography, see Appendix C).

Although WEPP: Road accounts for deposition based on the fill-slope and buffer characteristics, it is not clear how sediment delivery is calculated. The model does not allow the user to input important fill- or cut-slope characteristics such as vegetative cover. If buffer topography affects sediment input to a stream to a greater extent than road characteristics, as indicated by this study as well as by Rhee et al. (2004), more input should be related to fill-slope and buffer.

While the inputs may need some adjustment for tropical conditions, they are fairly comprehensive and easily definable. Users have the ability to estimate sediment production whether they have high detail or low detail data. Since it is easy to learn and free online, this would be an ideal model for land managers with limited resources.

5.1.2 SEDMODL

SEDMODL was a very easy model to use and understand. The simple equations allow the user to understand exactly how changes in inputs will affect the output. The inputs are general and easy to obtain. If time or resources prevent a field visit, GIS and satellite imagery could be used to estimate the inputs; the majority of inputs are assigned a factor based on a range of values rather than requiring an exact measurement. Although this is helpful if detailed data is not available, this generalization could reduce the accuracy of sediment estimation by overestimating or underestimating production based on the condition of the watershed and the precision of the data. In addition, the assignment of factor values is somewhat ambiguous and not given much scientific justification.

Two relatively vague factors included in the equation are road age factor and sediment delivery. Road age clearly affects erosion potential as recently constructed roads typically have a high amount of loose sediment available for transport. As the road ages and traffic regularly passes over the surface, the road often stabilizes and sediment is compacted. In SEDMODL however, the assigned factor value of a 10 versus a 2 depending on if the road was constructed in the past year, indicates there is significant improvement in the road condition after one year; this may not always be the case. In addition, the placing of this variable in the set of equations raises a question. Road age is multiplied by the sum of the sediment generated from the road tread and the cut-slope. Does road age affect cut-slope condition? And if so, how significant is this influence?

Sediment delivery is a difficult variable to define. SEDMODL allows the user to define it themselves, and provides guidance by relating delivery to the distance of the road to the stream. While this can be a good indicator of how much sediment reaches a stream, the range provided and the associated delivery ratios are not representative of actual sediment delivery. SEDMODL assumes that if a road is greater than 60 m from a stream, that no sediment will reach the stream. During times of heavy precipitation, runoff can have high volumes and velocities. If the road channelizes the flow, runoff will not only reach the stream, but it could generate more sediment along the way. Distance alone cannot predict sediment delivery. An input describing the condition of the fill-slope or delivery pathway is needed to truly estimate the amount of sediment reaching the stream.

The ease of use of SEDMODL recommends it for use in watersheds where background data is not available and where land managers may not have the experience or resources to use more comprehensive models.

5.1.3 STJ-EROS

Like SEDMODL, STJ-EROS utilizes a simple equation to estimate sediment yield. While one or two equations may not be as comprehensive as the algorithms involved in WEPP: Road, they may easier to use for land managers where internet is not available or where the English language is not readily understood. STJ-EROS was developed for sediment estimation in the Caribbean so the coefficients may be more applicable to the Corrego Horizonte watershed than those developed by WEPP: Road or SEDMODL. On the other hand, there are not as many user defined inputs so the equations are limited to the St. John Virgin Islands; if the climate parameters of that location are representative of other tropical watersheds there may not be an issue.

STJ-EROS only requires four inputs: road length, width, slope, and precipitation. While these factors are some of the most important, this model does not consider traffic, specific road surface characteristics, or the condition of the cut- and fill-slopes. In addition, the equation for estimating cut-slope is limited as it assumes the sediment generated is simply 9% of that produced by the road. This does not take into account basic factors such as the slope or vegetative cover of the cut-slope. Since STJ-EROS predicted negative sediment yields for some road segments in the Corrego Horizonte watershed, coefficients need to be adjusted and/or input value ranges extended for application to other locations.

As with SEDMODL, sediment delivery is a user defined value that is multiplied by the final sediment yield; STJ-EROS provides no guidance as to how it should be defined. While this model may be comprehensive in terms of the number and type of sediment sources identified, if the amount of sediment produced and delivered is not accurately estimated, the results will not be helpful for management purposes.

STJ-EROS is easy to use but may be to general to apply to other watersheds. Unlike the other models, it has not been applied to other locations. While this model may not be suitable for the Corrego Horizonte watershed, its ability to estimate sediment loading from a variety of sources on a watershed scale give it great potential.

5.2 Model comparison

Due to the variety of conditions of not only a road surface, but also the cut- and fill-slope, climate, watershed characteristics, and community, it is extremely difficult to design a model that accounts for all possible road network scenarios. The classification system developed for this study was designed specifically for this watershed although it may selectively be applied to other watersheds. Nothing can replace field observations when it comes to understanding erosion within a watershed and prioritizing areas for management. Time and financial constraints often limit first hand observations which make a classification system a useful tool. It can guide the user by identifying the factors that generate erosion and the types of evidence that indicate erosion.

Since sediment yield data is not available for the majority of tropical, developing watersheds, one of the ways to determine whether a model is applicable, is to compare how model outputs relate to field observations. Based on the evaluation of differences between model rankings and field rankings, WEPP: Road matched more closely to the field observations than SEDMODL and STJ-EROS. Although WEPP: Road had the most road segments with scores matching those of field observations, less than 50% of the road segments classified as having a high potential for erosion (scores 4 and 5) coordinated with field observations. STJ-EROS was able to predict some high priority road segments and had no segments that were grossly mismatched. SEDMODL had the highest number of road segments with scores opposite to those assigned by field observations and was unable to identify many of the road segments classified as highly erosive. The slight correlation between SEDMODL and STJ-EROS, supported by the R2 coefficient, does not necessarily mean these models are better at predicting sediment yield in the tropics. All three models require adjustment to input parameters to better reflect tropical conditions. The relative accuracy of these models in predicting high priority roads (scores 4 and 5) is important because ideally, any resources available would be allocated to the segments in these categories. Roads identified with high erosion and/or delivery potential may be considered the most detrimental to the environmental health of the watershed.

As with any model, it is important to understand that it is a tool that is only as good as the data going into it. Field observations are essential to determining management practices, but a useful model can aid in the process by decreasing time and cost. While the models evaluated in this study might be useful, it is clear that more work is needed to develop a road erosion prediction model specific to the tropics.

5.3 Research needs

One of the most glaring problems in each of the road erosion prediction models available today is that of calculating sediment delivery. An equation, algorithm, or set of criteria regarding sediment delivery need to be developed and adopted for erosion prediction methods. Research on erosion and sedimentation needs to focus not only on the sources and processes of erosion, but also on the delivery of the sediment generated. A study which calculates a range of sediment delivery ratios for a variety of conditions would be very useful for watershed models; roads are not the only source for which sediment delivery is an important issue. More related to road erosion, is the need to understand the interactions between the factors that generate erosion; we need to have a better understanding of the relationships between road construction, runoff, and drainage structure or how soil type, slope, and runoff characteristics influence sediment delivery. Although there have been studies done to research the individual processes involved in road erosion, such as the work by Ziegler et al. (2001, 2002, and 2004), these results need to be better incorporated into existing models.

Current erosion research should be focused in the tropics where the effects of contaminants such as sediment, impact the local community to a great extent. Sediment can impede such basic needs as transportation and water supply. There is a need for models which apply directly to the tropics, so that areas of concern can be identified and managed.

A better understanding of the sediment sources and interactions in a watershed will lead to better long-term soil and water conservation efforts. This type of research could provide the opportunity to link road maintenance with the valuation of ecosystem services in a watershed. By providing a model that demonstrates the significance of this linkage in a watershed, there will be added incentive to fund effective road maintenance. Thus, such research could open the door to explore the presently untapped connection between environmental sustainability, ecosystem services, and economic development. In the context of ecosystem services, these relationships must be defined and developed so that communities can receive the mutual benefits of implementing programs that incorporate environmental sustainability and infrastructure maintenance. While assigning an economic and environmental value to road protection is beyond the scope of this project, the goal of this research is to identify which models and techniques can be used towards this end.

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Appendix A. Slope Analysis

A.1. Statistical comparison of slope measurement methods

To use the chosen road erosion prediction models, the road network had to be divided into uniform road segments. This is primarily done based on the slope of the road (i.e breaks in slope indicate breaks in the road). A handheld ‘consumer’ GPS with nominal 3-5m accuracy was used in a tracking mode to store location and elevation along the road. First, it was necessary to determine whether the measurement of slope using GPS was significantly different than that of an actual field survey of the road segment. Dr. Marco Caiado and Brazilian students calculated the slope of four road segments using a topographical level. The average slope for each segment was compared to the slope measured by different methods of GPS. A statistical analysis using R was done to identify if there was a significant difference in the measurement of slope through topographical survey or by GPS. The null and alternative hypotheses were as follows:

$H_{O1}\colon \mu_S = \mu_{GPS}$: There is no significant difference in the value of slope as measured through survey (μ_s) or by GPS (μ_{GPS}).

$H_{A1}\colon \mu_S \neq \mu_{GPS}$: There is a significant difference in the value of slope as measured through survey (μ_s) or by GPS (μ_{GPS}).

Since the sample size for each group was only four, the data were assumed to be non-normal. A nonparametric paired Wilcox test with a Bonferonni correction (alpha of 0.017) was used. In the comparison of the survey data to that of various GPS methods, the p-value was greater than the stated alpha of 0.017 in all cases. This led to the acceptance of the null hypothesis that there was no significant difference in the measurement of slope between field survey and GPS.

Since there was no significant difference in the measurement of slope between field survey and GPS, it was determined that GPS could be used to calculate slope for each road segment. Five different methods of the GPS were used: manual points, points taken every second while walking, points taken every second while driving, points taken every 10 m while walking, and points taken every 10 m while driving. A second statistical analysis was performed to identify whether there was a significant difference in the measurement of slope using each GPS method. The null and alternative hypotheses were as follows

$H_{O2}: \mu_1 = \mu_2 = \mu_3 = \mu_4 = \mu_5$: There is no significant difference between the five methods of GPS slope measurement.

$H_{A2}: \mu_1 \neq \mu_2 \neq \mu_3 \neq \mu_4 \neq \mu_5$: There is a significant difference between the five methods of GPS slope measurement.

A random sample of 23 road segments was chosen with GIS to compare slopes measured by GPS. Not all GPS methods were applied to each road segment, so the samples chosen were those with greatest number and variety of points; each road segment had points from the manual method and three different track methods. Segments were selected by first identifying two GPS manual points along a road segment. The points from the GPS tracks between those two manual points were then identified. Slope was calculated for each set of points by dividing the change in elevation between the first and last point by the total distance between those points. One comprehensive statistical test was completed to compare the GPS manual points with the points taken every second while driving with the points taken every 10 m by walking. This test compares the overall differences between transportation methods and time/distance methods.

Due to the limited number of data points for each GPS method, normality of the data was tested on the residuals of the data. Normality was tested by plotting the residuals on a normal Q-Q plot (figure A.1) with R and by conducting a Shapiro Wilks normality test on the residuals with an alpha of 0.05. As shown in figure A.1, the data is skewed heavily at the tails, indicating that the data does not follow a normal distribution. In addition, the Shapiro Wilks test resulted in a p-value of 6.127e-05 which is less than the alpha of 0.05, leading to the rejection of the null hypothesis that each data set follows a normal distribution. To test for equal variance, the Fligner-Killeen test for non-normal data was used. The p-value was found to be 0.74 which is greater than an alpha of 0.05 so the null hypothesis of equal variance is accepted.

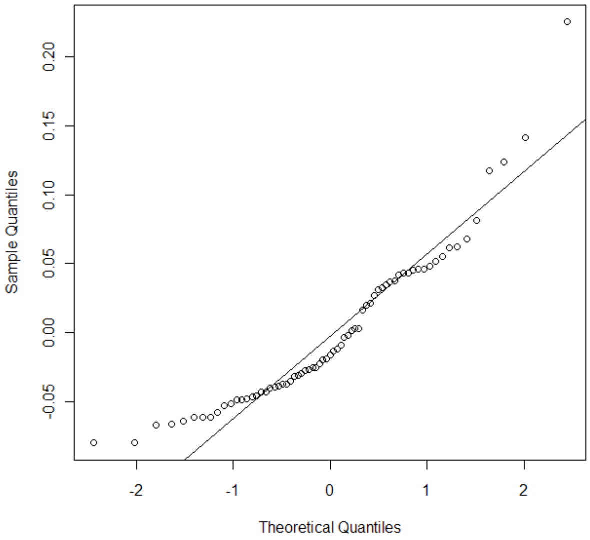

Figure A.1. Normal Q-Q plot of residual data from slope measurements.

Since the slope measurements are paired by location and do not follow a normal distribution, the nonparametric paired Wilcox test with a Bonferonni fix, and thus an alpha of 0.017, was applied for slope analysis. Since there are more than two data sets, a Bonferonni fix was necessary to reduce the chance of a Type I error. In addition, the data must be paired because each observation depends on the road segment (i.e location). The Wilcox test requires that the data is from the same distribution. Q-Q plots were used to test for this assumption. The Q-Q plots shown in figure A.2 illustrate that the data appear to follow the same distribution.

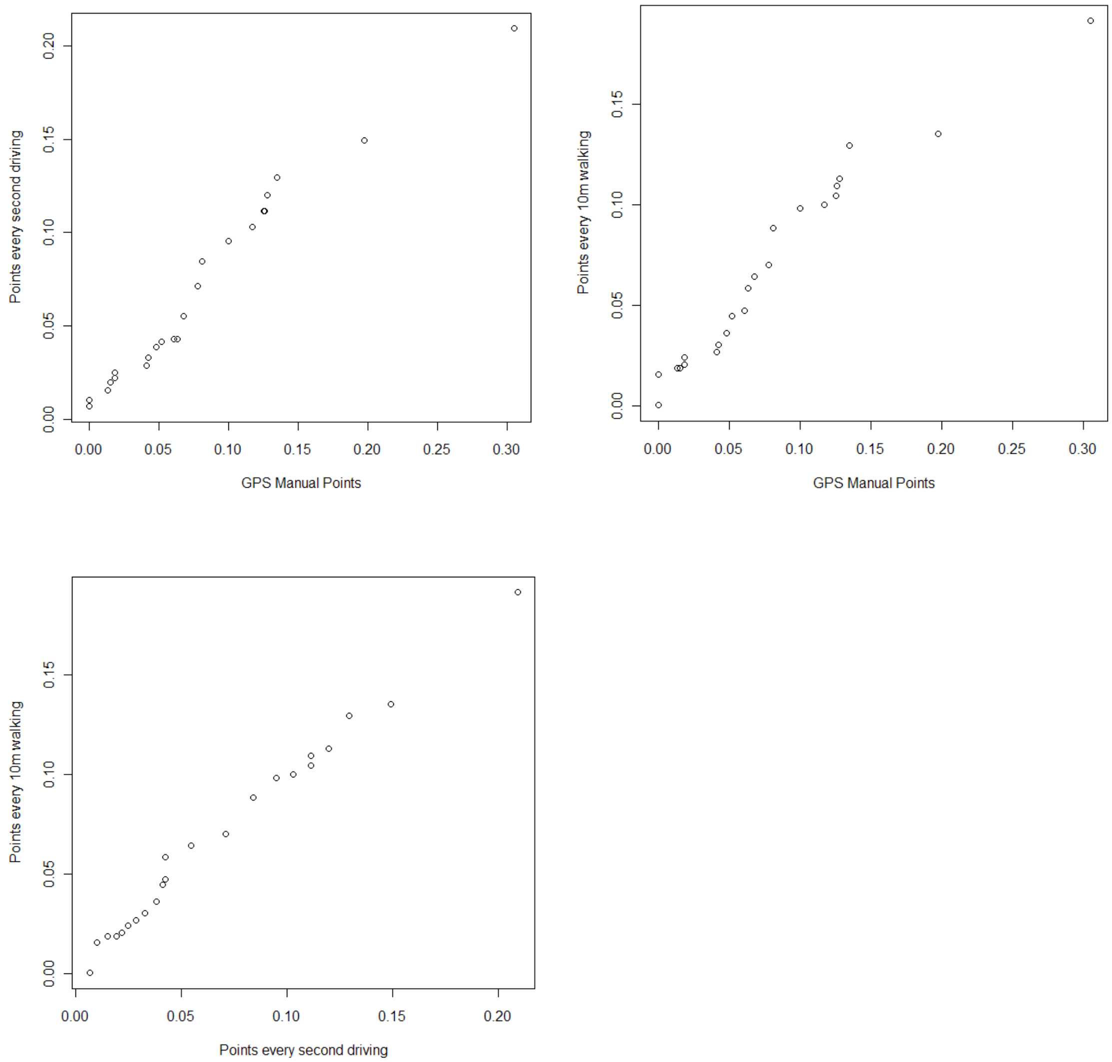

Figure A.2. Q-Q plots of slope measurements from three GPS methods (from top left to bottom left: GPS manual points vs. Points every second while driving; GPS manual points vs. Points every 10 m while walking; Points every second while driving vs. Points every 10 m while walking)

Shown in table A.1 is a summary of p-values for each test. As shown in the table, all p-values were greater than the stated alpha of 0.017, thus the null hypothesis was accepted, concluding that there is no significant difference in slope measurements using various GPS methods.

Table A.1. Summary of p-values for pairwise comparison of slope data.

Pairwise comparison of slope	p-value (alpha = 0.017)
Manual points vs. Points taken every second while driving	0.41
Manual points vs. Points taken every 10m while walking	0.34
Points taken every second while driving vs. Points taken every 10m while walking	0.58

A.2 Summary of slope data and statistical coding

Table A.2 summarizes the slope data used in the statistical analysis. Each road segment is described by the first and last GPS manual points.

Table A.2. Summary of slope data from the road network in the Corrego Horizonte.

Road Segment	Slope from GPS Manual Points	Slope from points taken every second while driving	Slope from points taken every 10 m while walking	Slope from field survey
831-832	0.14	0.12	0.11	n/a
829-830	0.02	0.02	0.03	0.02
821-823	0.13	0.11	0.11	n/a
818-897	0.31	0.13	0.13	0.13
804-806	0.05	0.10	0.10	0.17
801-804	0.08	0.04	0.03	n/a
798-799	0.04	0.04	0.05	n/a
815-817	0.00	0.02	0.02	0.03
790-792	0.08	0.08	0.09	n/a
787-788	0.00	0.04	0.02	n/a
788-789	0.13	0.15	0.14	n/a
759-760	0.06	0.07	0.06	n/a
760-761	0.10	0.11	0.10	n/a
763-764	0.06	0.03	0.04	n/a
766-767	0.05	0.04	0.07	n/a
764-765	0.02	0.03	0.02	n/a
765-766	0.04	0.02	0.02	n/a
767-768	0.01	0.01	0.02	n/a
770-771	0.12	0.02	0.04	n/a
774-775	0.20	0.21	0.19	n/a
844-846	0.07	0.05	0.06	n/a
841-842	0.13	0.10	0.10	n/a
839-840	0.02	0.01	0.00	n/a

The following is a summary of commands in R used to complete the statistical analysis on slope.

```
> y<-read.csv("output.csv")
> attach(y)
> names(y)
[1] "Yield"   "Group"   "Slope1"  "Method1" "Slope2"  "Method2"
> boxplot(Slope1~Method1)
> means.method<-tapply(Slope1,Method1,mean,na.rm=TRUE)
> residuals<-Slope1-means.method[Method1]
> qqnorm(residuals)
> qqline(residuals)
> shapiro.test(residuals)
      Shapiro-Wilk normality test
data:  residuals
W = 0.9037, p-value = 6.127e-05
```

Equal Variance Test (alpha 0.05)

```
> fligner.test(Slope1, Method1)
      Fligner-Killeen test of homogeneity of variances

data:  Slope1 and Method1
Fligner-Killeen:med chi-squared = 0.5935, df = 2, p-value = 0.7432
```

Paired Wilcox Test for GPS and field measurements with Bonferonni Fix (alpha 0.0167)

```
> s<-read.csv("slope.csv")
> attach(s)
> names(s)
[1] "survey" "gps"    "gps2"   "gps3"
> wilcox.test(survey,gps,paired=TRUE)

      Wilcoxon signed rank test

data:  survey and gps
V = 6, p-value = 0.875
alternative hypothesis: true location shift is not equal to 0

> wilcox.test(survey,gps2,paired=TRUE)

      Wilcoxon signed rank test

data:  survey and gps2
V = 7, p-value = 0.625
```

```
alternative hypothesis: true location shift is not equal to 0

> wilcox.test(survey,gps3,paired=TRUE)

        Wilcoxon signed rank test

data:  survey and gps3
V = 7, p-value = 0.625
alternative hypothesis: true location shift is not equal to 0
```

Paired Wilcox Test for GPS slope methods with Bonferonni Fix (alpha 0.0167)

```
> s<-read.csv("slope.csv")
> attach(s)
> names(s)
[1] "GPSA"    "SecondA" "X10mA"   "GPSB"    "SecB"    "X10mB"    “GPSC”  “SecC”
“X10mC”
> wilcox.test(GPSA,SecondA,paired=TRUE)
        Wilcoxon signed rank test
data:  GPSA and SecondA
V = 166, p-value = 0.41
alternative hypothesis: true location shift is not equal to 0

> wilcox.test(GPSA,X10mA,paired=TRUE)
        Wilcoxon signed rank test
data:  GPSA and X10mA
V = 170, p-value = 0.3447
alternative hypothesis: true location shift is not equal to 0

> wilcox.test(SecondA,X10mA,paired=TRUE)
        Wilcoxon signed rank test
data:  SecondA and X10mA
V = 157, p-value = 0.5803
alternative hypothesis: true location shift is not equal to 0

> wilcox.test(GPSB,X10mB,paired=TRUE)
        Wilcoxon signed rank test
data:  GPSB and X10mB
V = 50, p-value = 0.4238
alternative hypothesis: true location shift is not equal to 0

> wilcox.test(GPSB,SecB,paired=TRUE)
        Wilcoxon signed rank test
data:  GPSB and SecB
V = 58, p-value = 0.1514
alternative hypothesis: true location shift is not equal to 0
```

```
> wilcox.test(X10mB,SecB,paired=TRUE)
        Wilcoxon signed rank test
data:  X10mB and SecB
V = 55, p-value = 0.2334
alternative hypothesis: true location shift is not equal to 0

> wilcox.test(GPSC,X10mC,paired=TRUE)
        Wilcoxon signed rank test
data:  GPSC and X10mC
V = 60, p-value = 0.6698
alternative hypothesis: true location shift is not equal to 0

> wilcox.test(GPSC,SecC,paired=TRUE)
        Wilcoxon signed rank test
data:  GPSC and SecC
V = 67, p-value = 0.391
alternative hypothesis: true location shift is not equal to 0

> wilcox.test(X10mC,SecC,paired=TRUE)
        Wilcoxon signed rank test
data:  X10mC and SecC
V = 48, p-value = 0.8077
alternative hypothesis: true location shift is not equal to 0
```

Appendix B. Model Input Documentation

B.1 Summary of Model Inputs

B.1.1 WEPP: Road model inputs

All road parameters were organized using Microsoft Excel. The online interface of WEPP: Road accepts input by excel. Table B.1 summarizes the parameters assigned to each road segment within the Corrego Horizonte watershed and run using WEPP: Road.

Table B.1. Summary of WEPP: Road model inputs

Road Id	Road Design	Road Surface	Traffic Level	Road Gradient (%)	Road Length (m)	Road Width (m)	Fill gradient (%)	Fill length (m)	Buffer gradient (%)	Buffer length (m)	Rock Fragment (%)
106	OU	N	H	3	119	4.5	2	20	0.1	0.3	0
1	OU	N	H	1.8	191	4.5	2	20	0.1	0.3	0
2	OU	N	H	3.6	144	4.5	2	20	0.1	0.3	0
4	OU	N	H	0.4	217	4.5	2	20	0.1	0.3	0
3	OU	N	H	0.1	141	4.5	2	20	0.1	0.3	0
5	OU	N	H	1.1	148	4.5	2	20	0.1	0.3	0
91	OR	N	H	2.4	130	4.5	0.1	0.5	0.1	0.3	0
6	OR	N	H	2.5	211	4.5	0.5	10	0.1	0.3	0
7	OR	N	H	2.4	190	4.5	0.5	30	0.1	0.3	0
107	OR	N	H	9	119	4.5	0.5	30	0.1	0.3	0
108	OR	N	H	4	97	4.5	1	70	0.1	0.3	0
8	OR	N	H	3.9	239	4.5	1	70	0.1	0.3	0
92	OR	N	H	0.2	99	4.5	1	70	0.1	0.3	0
9	OR	N	H	5	128	4.5	0.5	10	0.1	0.3	0
93	OR	N	H	1.7	60	4.5	0.5	0.5	0.1	0.3	0
10	OU	N	H	0.3	86	4.5	0.5	0.5	80	10	0
94	OR	N	H	19.3	55	4.5	0.2	0.3	90	10	5
11	OR	N	H	4.1	145	4.5	0.1	2	90	10	0
12	OU	N	L	8.3	128	2.5	1	20	0.1	0.3	0
13	OR	N	H	9.7	229	4.5	20	40	0.1	0.3	0

Table B.1. continued

Road Id	Road Design	Road Surface	Traffic Level	Road Gradient (%)	Road Length (m)	Road Width (m)	Fill gradient (%)	Fill length (m)	Buffer gradient (%)	Buffer length (m)	Rock Fragment (%)
14	OR	N	H	7.3	258	4.5	50	40	0.1	0.3	0
95	OR	N	H	6.1	101	6	50	40	0.1	0.3	0
15	OR	N	H	4.8	230	6	50	100	0.1	0.3	0
96	OU	N	H	1.9	77	4.5	80	100	0.1	0.3	0
97	OU	N	H	12.5	41	4.5	80	100	0.1	0.3	0
16	OU	N	H	7.2	258	4.5	50	100	0.1	0.3	0
17	OR	N	H	3	297	5.5	50	100	0.1	0.3	0
18	OR	N	H	9.3	202	4.5	50	70	0.1	0.3	0
109	OR	N	H	5.5	135	4.5	50	70	0.1	0.3	0
98	OR	N	H	7.1	258	4.5	50	70	0.1	0.3	0
99	OR	N	H	4.7	51	5	50	70	0.1	0.3	0
100	OR	N	H	6.2	123	5	50	50	0.1	0.3	0
19	OR	N	H	13.7	220	5.5	50	30	0.1	0.3	0
110	OR	N	H	12.4	180	5.5	50	30	0.1	0.3	0
101	OR	N	H	16.4	88	4.5	80	30	0.1	0.3	0
102	OU	N	H	3.6	143	4.5	50	30	0.1	0.3	0
20	OR	N	H	3.5	226	4.5	2	10	0.1	0.3	0
21	OR	N	L	2	213	4.5	0.5	10	0.1	0.3	0
22	OR	N	L	6.2	220	4.5	0.1	0.3	60	50	5
23	OR	N	L	11.2	27	4.5	0.1	0.3	50	50	0
24	OR	N	L	0.1	94	4.5	0.1	0.3	50	30	0
25	OR	N	H	6.2	109	6	50	20	0.1	0.3	0
26	OR	N	H	9.4	132	6	0.1	0.5	50	30	0
27	OR	N	H	7.3	120	6	2	20	0.1	0.3	0
28	OR	N	H	8.7	139	6	0.5	0.5	0.1	0.3	0
103	OR	N	H	12.6	51	6	40	40	0.1	0.3	0
29	OR	N	H	14.6	79	6	30	40	0.1	0.3	0
30	OR	N	H	2.5	210	4.5	5	20	0.1	0.3	0

Table B.1. continued

Road Id	Road Design	Road Surface	Traffic Level	Road Gradient (%)	Road Length (m)	Road Width (m)	Fill gradient (%)	Fill length (m)	Buffer gradient (%)	Buffer length (m)	Rock Fragment (%)
31	OR	N	L	12.5	86	4.5	3	100	0.1	0.3	0
32	OR	N	L	4.2	85	4.5	3	20	0.1	0.3	0
33	OR	N	L	3.9	92	4.5	3	20	0.1	0.3	0
34	OR	N	L	3.6	54	4.5	3	20	0.1	0.3	0
35	OR	N	L	3.4	83	4.5	3	20	0.1	0.3	0
36	OR	N	L	6.1	64	4.5	0.5	20	0.1	0.3	0
37	OR	N	L	4.3	131	4.5	2	20	0.1	0.3	0
38	OR	N	L	10.4	92	5	2	20	0.1	0.3	0
104	OR	N	L	7	60	4.5	5	10	0.1	0.3	0
39	OU	N	L	3.8	127	4.5	5	20	0.1	0.3	0
40	OU	N	L	3.4	103	4.5	2	100	0.1	0.3	0
41	OU	N	L	0.1	98	4.5	2	100	0.1	0.3	0
42	OU	N	L	2.8	42	4.5	2	100	0.1	0.3	0
43	OU	N	L	2.1	63	4.5	2	100	0.1	0.3	0
44	OU	N	L	8	71	4.5	2	100	0.1	0.3	0
45	OR	N	L	5.8	18	4.5	4	100	0.1	0.3	0
46	OR	N	L	9.6	56	4.5	4	100	0.1	0.3	0
47	OR	N	L	3	61	4.5	2	100	0.1	0.3	0
48	OR	N	L	8.8	43	4.5	5	50	0.1	0.3	0
49	OR	N	L	8.3	55	4.5	5	50	0.1	0.3	0
50	OR	N	L	5.6	116	4.5	2	100	0.1	0.3	0
51	OU	N	L	0.7	100	4.5	2	100	0.1	0.3	0
52	OU	N	L	5.4	173	4.5	2	100	0.1	0.3	0
53	OR	N	L	1.4	133	4.5	2	100	0.1	0.3	0
54	OR	N	L	4.5	70	4.5	2	100	0.1	0.3	0
55	OR	N	L	1.7	211	4.5	2	100	0.1	0.3	0
56	OR	N	L	0.6	52	4.5	2	100	0.1	0.3	0
57	OR	N	L	6.8	113	4.5	2	100	0.1	0.3	0

Table B.1. continued

Road Id	Road Design	Road Surface	Traffic Level	Road Gradient (%)	Road Length (m)	Road Width (m)	Fill gradient (%)	Fill length (m)	Buffer gradient (%)	Buffer length (m)	Rock Fragment (%)
58	OR	N	L	33.3	34	4.5	2	100	0.1	0.3	0
59	OR	N	L	5.9	19	4.5	2	100	0.1	0.3	0
60	OR	N	L	10.6	39	4.5	2	100	0.1	0.3	0
111	OU	N	L	15.4	134	4.5	15	100	0.1	0.3	0
61	OU	N	L	14.6	194	4.5	15	100	0.1	0.3	0
62	OU	N	L	2.1	96	4.5	2	100	0.1	0.3	0
63	OU	N	L	8	31	4.5	2	10	0.1	0.3	0
64	OU	N	L	3.2	280	4.5	20	30	0.1	0.3	0
65	OR	N	L	2.7	239	4.5	2	40	0.1	0.3	0
66	OR	N	L	2.5	175	4.5	2	10	0.1	0.3	0
67	OR	N	L	5.2	94	4.5	2	40	0.1	0.3	0
68	OU	N	L	6	153	4.5	0.5	40	0.1	0.3	0
69	OU	N	L	15.5	109	4.5	2	40	0.1	0.3	0
112	OU	N	L	0.9	234	4.5	50	30	0.1	0.3	0
70	OU	N	L	2.5	275	4.5	50	30	0.1	0.3	0
71	OU	N	L	12.4	244	4.5	2	10	0.1	0.3	0
72	OU	N	L	0.4	101	4.5	2	30	0.1	0.3	0
73	OU	N	L	2.5	80	4.5	2	30	0.1	0.3	0
74	OU	N	L	3.6	24	4.5	5	100	0.1	0.3	0
75	OU	N	L	7.1	240	4.5	5	100	0.1	0.3	0
76	OU	N	L	9.1	83	4.5	0.5	20	0.1	0.3	0
113	OU	N	L	3.9	185	5	1	20	0.1	0.3	0
77	OU	N	L	6.5	252	5	3	20	0.1	0.3	0
105	OU	N	L	8.6	147	6	10	20	0.1	0.3	0
78	OU	N	L	10.2	158	6	10	70	0.1	0.3	0
79	OU	N	L	6	59	4.5	0.5	70	0.1	0.3	0
80	OU	N	L	6.9	238	4.5	5	70	0.1	0.3	0

Table B.1. continued

Road Id	Road Design	Road Surface	Traffic Level	Road Gradient (%)	Road Length (m)	Road Width (m)	Fill gradient (%)	Fill length (m)	Buffer gradient (%)	Buffer length (m)	Rock Fragment (%)
114	OU	N	L	6.5	174	4.5	5	40	0.1	20	0
81	OU	N	L	1.6	106	4.5	2	100	0.1	10	0
82	OU	N	L	3.1	103	4.5	0.5	100	0.1	0.3	0
83	OU	N	L	0.3	75	4.5	0.5	100	0.1	0.3	0
84	OU	N	N	19.9	151	4.5	10	100	0.1	0.3	1
85	OR	N	L	5.9	204	4.5	5	50	0.1	0.3	1
86	OR	N	L	10	219	6	0.1	1	10	40	0
87	OR	N	L	12.7	214	6	0.1	0.5	50	0.5	0
88	OR	N	L	9.6	65	4.5	2	3	50	10	5
89	OR	N	L	4.6	117	4.5	0.1	0.5	80	5	2
90	OR	N	L	4.5	101	4.5	5	100	0.1	0.3	0

B.1.2 SEDMODL model inputs

Microsoft excel was used to organize each of the road parameters required by SEDMODL. Table B.2 summarizes these parameters used in the SEDMODL equations.

Table B.2. Summary of SEDMODL model inputs

Road Id	Length (m)	Width (m)	Gradient	Surface	Traffic	Age	Cut-slope Cover	Cut-slope height (m)	Precipitation	Erosion Rate (t/m^2)	Sediment Delivery	Tread Sediment (t/y)	CutSlope Sediment (t/y)
106	119	4.5	0.2	1	10	2	0.1023	7.5	0.87515	0.0037	1	3.47	0.34
1	191	4.5	0.2	1	10	2	0.1023	7.5	0.87515	0.0037	1	5.57	0.54
2	144	4.5	0.2	1	10	2	0.1023	7.5	0.87515	0.0037	1	4.20	0.41
4	217	4.5	0.2	1	10	2	0.254	7.5	0.87515	0.0037	1	6.32	1.53
3	141	4.5	0.2	1	10	2	0.1023	7.5	0.87515	0.0037	1	4.11	0.40
5	148	4.5	0.2	1	10	2	0.1023	7.5	0.87515	0.0037	1	4.31	0.42
91	130	4.5	0.2	2	10	2	0.1023	0.75	0.87515	0.0037	1	7.58	0.04
6	211	4.5	0.2	2	10	2	0.1023	0.75	0.87515	0.0037	1	12.30	0.06
7	190	4.5	0.2	2	2	2	0.1023	0.75	0.87515	0.0037	0.35	0.78	0.02
107	119	4.5	1	2	2	2	0.1023	0.75	0.87515	0.0037	0.35	2.43	0.01
108	97	4.5	0.2	2	2	2	0.1023	7.5	0.87515	0.0037	0.05	0.06	0.01
8	239	4.5	0.2	2	2	2	0.1023	7.5	0.87515	0.0037	0.05	0.14	0.03
92	99	4.5	0.2	2	2	2	0.5222	7.5	0.87515	0.0037	0.05	0.06	0.07
9	128	4.5	0.2	2	2	2	0.1023	0.75	0.87515	0.0037	1	1.49	0.04
93	60	4.5	0.2	2	2	2	0.1023	0.75	0.87515	0.0037	1	0.70	0.02
10	86	4.5	0.2	1	2	2	0.1023	0.75	0.87515	0.0037	1	0.50	0.02
94	55	4.5	2.5	2	1	2	0.3742	7.5	0.87515	0.0037	1	4.01	0.57
11	145	4.5	0.2	2	1	2	0.3742	7.5	0.87515	0.0037	1	0.85	1.51
12	128	2.5	1	1	1	2	0.1023	7.5	0.87515	0.0037	1	1.04	0.36
13	229	4.5	1	2	2	2	0.15	3	0.87515	0.0037	0.35	4.67	0.13
14	258	4.5	1	2	2	2	0.15	7.5	0.87515	0.0037	0.35	5.26	0.38
95	101	6	1	2	2	2	0.254	7.5	0.87515	0.0037	0.35	2.75	0.25
15	230	6	0.2	2	2	2	0.254	7.5	0.87515	0.0037	0.05	0.18	0.08

Table B.2. continued

Road Id	Length (m)	Width (m)	Gradient	Surface	Traffic	Age	Cut-slope Cover	Cut-slope height (m)	Precipitation	Erosion Rate (t/m^2)	Sediment Delivery	Tread Sediment (t/y)	CutSlope Sediment (t/y)
96	77	4.5	0.2	1	2	2	0.1023	7.5	0.87515	0.0037	0.05	0.02	0.01
97	41	4.5	2.5	1	2	2	0.1023	7.5	0.87515	0.0037	0.05	0.15	0.01
16	258	4.5	1	1	2	2	0.1023	7.5	0.87515	0.0037	0.05	0.38	0.04
17	297	5.5	0.2	2	2	2	0.1023	7.5	0.87515	0.0037	0.05	0.21	0.04
18	202	4.5	1	2	2	2	0.254	7.5	0.87515	0.0037	0.05	0.59	0.07
109	135	4.5	1	2	2	2	0.254	7.5	0.87515	0.0037	0.05	0.39	0.05
98	258	4.5	1	2	2	2	0.1023	7.5	0.87515	0.0037	0.05	0.75	0.04
99	51	5	0.2	2	2	2	0.4435	7.5	0.87515	0.0037	0.05	0.03	0.03
100	123	5	1	2	2	2	0.1023	7.5	0.87515	0.0037	0.35	2.79	0.12
19	220	5.5	2.5	2	2	2	0.4435	7.5	0.87515	0.0037	0.35	13.71	0.95
110	180	5.5	2.5	2	2	2	0.4435	7.5	0.87515	0.0037	0.35	11.22	0.78
101	88	4.5	2.5	2	2	2	0.3742	7.5	0.87515	0.0037	0.35	4.49	0.32
102	143	4.5	0.2	1	2	2	0.1023	7.5	0.87515	0.0037	0.35	0.29	0.14
20	226	4.5	0.2	2	2	2	0.1023	0.75	0.87515	0.0037	1	2.63	0.06
21	213	4.5	0.2	2	1	2	0.1023	0.75	0.87515	0.0037	1	1.24	0.06
22	220	4.5	1	2	1	2	0.1023	7.5	0.87515	0.0037	0.35	2.24	0.22
23	27	4.5	2.5	2	1	2	0.1023	7.5	0.87515	0.0037	0.35	0.69	0.03
24	94	4.5	0.2	2	1	2	0.1023	7.5	0.87515	0.0037	0.35	0.19	0.09
25	109	6	1	2	2	2	0.77	7.5	0.87515	0.0037	1	8.47	2.33
26	132	6	1	2	2	2	0.3742	7.5	0.87515	0.0037	0.35	3.59	0.48
27	120	6	1	2	2	2	0.4435	0.75	0.87515	0.0037	1	9.33	0.15
28	139	6	1	2	2	2	0.6155	0.75	0.87515	0.0037	1	10.80	0.24
103	51	6	2.5	2	2	2	0.6155	7.5	0.87515	0.0037	0.35	3.47	0.30
29	79	6	2.5	2	2	2	0.15	7.5	0.87515	0.0037	0.35	5.37	0.12
30	210	4.5	0.2	2	1	2	0.15	7.5	0.87515	0.0037	1	1.22	0.87
31	86	4.5	2.5	2	1	2	0.4435	7.5	0.87515	0.0037	0.05	0.31	0.05
32	85	4.5	0.2	2	1	2	0.1023	7.5	0.87515	0.0037	1	0.50	0.24

Table B.2. continued

Road Id	Length (m)	Width (m)	Gradient	Surface	Traffic	Age	Cut-slope Cover	Cut-slope height (m)	Precipitation	Erosion Rate (t/m^2)	Sediment Delivery	Tread Sediment (t/y)	CutSlope Sediment (t/y)
33	92	4.5	0.2	2	1	2	0.1023	7.5	0.87515	0.0037	1	0.54	0.26
34	54	4.5	0.2	2	1	2	0.1023	7.5	0.87515	0.0037	1	0.31	0.15
35	83	4.5	0.2	2	1	2	0.1023	7.5	0.87515	0.0037	1	0.48	0.24
36	64	4.5	1	2	1	2	0.1023	0.75	0.87515	0.0037	1	1.87	0.02
37	131	4.5	0.2	2	1	2	0.1023	3	0.87515	0.0037	1	0.76	0.15
38	92	5	2.5	2	1	2	0.3742	7.5	0.87515	0.0037	1	7.45	0.96
104	60	4.5	1	2	1	2	0.3742	7.5	0.87515	0.0037	1	1.75	0.62
39	127	4.5	0.2	1	1	2	0.77	7.5	0.87515	0.0037	1	0.37	2.71
40	103	4.5	0.2	1	1	2	0.3742	7.5	0.87515	0.0037	0.05	0.02	0.05
41	98	4.5	0.2	1	1	2	0.3742	7.5	0.87515	0.0037	0.05	0.01	0.05
42	42	4.5	0.2	1	1	2	0.3742	7.5	0.87515	0.0037	0.05	0.01	0.02
43	63	4.5	0.2	1	1	2	0.3742	7.5	0.87515	0.0037	0.05	0.01	0.03
44	71	4.5	1	1	1	2	0.3742	7.5	0.87515	0.0037	0.05	0.05	0.04
45	18	4.5	1	2	1	2	0.1023	0.75	0.87515	0.0037	0.05	0.03	0.00
46	56	4.5	1	2	1	2	0.1023	75	0.87515	0.0037	0.05	0.08	0.08
47	61	4.5	0.2	2	1	2	0.1023	0.75	0.87515	0.0037	0.05	0.02	0.00
48	43	4.5	1	2	1	2	0.3742	7.5	0.87515	0.0037	0.35	0.44	0.16
49	55	4.5	1	2	1	2	0.3742	7.5	0.87515	0.0037	0.35	0.56	0.20
50	116	4.5	1	2	1	2	0.3742	7.5	0.87515	0.0037	0.05	0.17	0.06
51	100	4.5	0.2	2	1	2	0.3742	7.5	0.87515	0.0037	0.05	0.03	0.05
52	173	4.5	1	2	1	2	0.1023	7.5	0.87515	0.0037	0.05	0.25	0.02
53	133	4.5	0.2	1	1	2	0.15	0.75	0.87515	0.0037	0.05	0.02	0.00
54	70	4.5	0.2	1	1	2	0.15	0.75	0.87515	0.0037	0.05	0.01	0.00
55	211	4.5	0.2	1	1	2	0.15	0.75	0.87515	0.0037	0.05	0.03	0.00
56	52	4.5	0.2	1	1	2	0.15	0.75	0.87515	0.0037	0.05	0.01	0.00
57	113	4.5	1	1	1	2	0.15	0.75	0.87515	0.0037	0.05	0.08	0.00
58	34	4.5	2.5	1	1	2	0.15	0.75	0.87515	0.0037	0.05	0.06	0.00

Table B.2. continued

Road Id	Length (m)	Width (m)	Gradient	Surface	Traffic	Age	Cut-slope Cover	Cut-slope height (m)	Precipitation	Erosion Rate (t/m^2)	Sediment Delivery	Tread Sediment (t/y)	CutSlope Sediment (t/y)
59	19	4.5	1	1	1	2	0.15	0.75	0.87515	0.0037	0.05	0.01	0.00
60	39	4.5	2.5	1	1	2	0.15	0.75	0.87515	0.0037	0.05	0.07	0.00
111	134	4.5	2.5	1	1	2	0.77	3	0.87515	0.0037	0.05	0.24	0.06
61	194	4.5	2.5	1	1	2	0.77	3	0.87515	0.0037	0.05	0.35	0.08
62	96	4.5	0.2	1	1	2	0.77	0.75	0.87515	0.0037	0.05	0.01	0.01
63	31	4.5	1	1	1	2	0.77	0.75	0.87515	0.0037	1	0.45	0.07
64	280	4.5	0.2	1	1	2	0.15	7.5	0.87515	0.0037	0.35	0.29	0.41
65	239	4.5	0.2	2	1	2	0.5222	7.5	0.87515	0.0037	0.35	0.49	1.21
66	175	4.5	0.2	2	1	2	0.5222	7.5	0.87515	0.0037	1	1.02	2.54
67	94	4.5	1	2	1	2	0.5222	7.5	0.87515	0.0037	0.35	0.96	0.48
68	153	4.5	1	1	1	2	0.5222	7.5	0.87515	0.0037	0.35	0.78	0.78
69	109	4.5	2.5	1	1	2	0.5222	7.5	0.87515	0.0037	0.35	1.39	0.55
112	234	4.5	0.2	1	1	2	0.5222	7.5	0.87515	0.0037	0.35	0.24	1.19
70	275	4.5	0.2	1	1	2	0.5222	7.5	0.87515	0.0037	0.35	0.28	1.39
71	244	4.5	2.5	1	1	2	0.5222	7.5	0.87515	0.0037	1	8.89	3.54
72	101	4.5	0.2	1	1	2	0.5222	7.5	0.87515	0.0037	0.35	0.10	0.51
73	80	4.5	0.2	1	1	2	0.5222	7.5	0.87515	0.0037	0.35	0.08	0.41
74	24	4.5	0.2	1	1	2	0.5222	7.5	0.87515	0.0037	0.05	0.00	0.02
75	240	4.5	1	1	1	2	0.5222	7.5	0.87515	0.0037	0.05	0.17	0.17
76	83	4.5	1	1	1	2	0.5222	0.75	0.87515	0.0037	1	1.21	0.12
113	185	5	0.2	1	2	2	0.1023	0.75	0.87515	0.0037	1	1.20	0.05
77	252	5	1	1	2	2	0.1023	0.75	0.87515	0.0037	1	8.16	0.07
105	147	6	1	1	2	2	0.1023	7.5	0.87515	0.0037	1	5.71	0.42
78	158	6	2.5	1	2	2	0.1023	7.5	0.87515	0.0037	0.05	0.77	0.02
79	59	4.5	1	1	1	2	0.1023	0.75	0.87515	0.0037	0.05	0.04	0.00
80	238	4.5	1	1	1	2	0.1023	7.5	0.87515	0.0037	0.05	0.17	0.03
114	174	4.5	1	1	1	2	0.1023	7.5	0.87515	0.0037	0.05	0.13	0.02

Table B.2. continued

Road Id	Length (m)	Width (m)	Gradient	Surface	Traffic	Age	Cut-slope Cover	Cut-slope height (m)	Precipitation	Erosion Rate (t/m^2)	Sediment Delivery	Tread Sediment (t/y)	CutSlope Sediment (t/y)
81	106	4.5	0.2	1	1	2	0.1023	7.5	0.87515	0.0037	0.05	0.02	0.02
82	103	4.5	0.2	1	1	2	0.1023	7.5	0.87515	0.0037	0.05	0.02	0.01
83	75	4.5	0.2	1	1	2	0.1023	7.5	0.87515	0.0037	0.05	0.01	0.01
84	151	4.5	2.5	1	0.1	2	0.1023	7.5	0.87515	0.0037	0.05	0.03	0.02
85	204	4.5	1	2	1	2	0.15	7.5	0.87515	0.0037	0.35	2.08	0.30
86	219	6	1	2	1	2	0.4435	7.5	0.87515	0.0037	0.35	2.98	0.94
87	214	6	2.5	2	1	2	0.4435	7.5	0.87515	0.0037	1	20.79	2.63
88	65	4.5	1	2	1	2	0.4435	7.5	0.87515	0.0037	1	1.89	0.80
89	117	4.5	0.2	2	1	2	0.3742	7.5	0.87515	0.0037	1	0.68	1.21
90	101	4.5	0.2	2	1	2	0.4435	7.5	0.87515	0.0037	0.05	0.03	0.06

B.1.3 STJ-EROS model inputs

Microsoft excel was also used to organize the road parameters for use by STJ-EROS. Table B.3 summarizes the inputs for the equations of STJ-EROS.

Table B.3. Summary of STJ-EROS model inputs

Road Id	Length (m)	Width (m)	Slope	Rainfall (cm)	Ungraded Road (kg/yr)	Sediment Delivery	Cutslope (kg/yr)	Sediment (t/yr)
106	119	4.5	0.03	129	503.80	1	45.34	0.55
1	191	4.5	0.018	129	150.05	1	13.50	0.16
2	144	4.5	0.036	129	901.42	1	81.13	0.98
4	217	4.5	0.01	129	-210.19	1	-18.92	-0.23
3	141	4.5	0.01	129	-136.58	1	-12.29	-0.15
5	148	4.5	0.011	129	-115.16	1	-10.36	-0.13
91	130	4.5	0.024	129	312.15	1	28.09	0.34
6	211	4.5	0.025	129	568.06	1	51.13	0.62
7	190	4.5	0.024	129	456.21	0.35	41.06	0.17

Table B.3. continued

Road Id	Length (m)	Width (m)	Slope	Rainfall (cm)	Ungraded Road (kg/yr)	Sediment Delivery	Cutslope (kg/yr)	Sediment (t/yr)
107	119	4.5	0.09	129	3720.56	0.35	334.85	1.42
108	97	4.5	0.04	129	747.84	0.05	67.31	0.04
8	239	4.5	0.039	129	1754.29	0.05	157.89	0.10
92	99	4.5	0.01	129	-95.89	0.05	-8.63	-0.01
9	128	4.5	0.05	129	1491.53	1	134.24	1.63
93	60	4.5	0.017	129	32.38	1	2.91	0.04
10	86	4.5	0.01	129	-83.30	1	-7.50	-0.09
94	55	4.5	0.193	129	5659.99	1	509.40	6.17
11	145	4.5	0.041	129	1172.17	1	105.50	1.28
12	128	2.5	0.083	129	1951.07	1	175.60	2.13
13	229	4.5	0.097	129	8071.20	0.35	726.41	3.08
14	258	4.5	0.073	129	5738.97	0.35	516.51	2.19
95	101	6	0.061	129	2217.92	0.35	199.61	0.85
15	230	6	0.048	129	3320.98	0.05	298.89	0.18
96	77	4.5	0.019	129	79.97	0.05	7.20	0.00
97	41	4.5	0.125	129	2155.86	0.05	194.03	0.12
16	258	4.5	0.072	129	5609.79	0.05	504.88	0.31
17	297	5.5	0.03	129	1536.80	0.05	138.31	0.08
18	202	4.5	0.093	129	6656.45	0.05	599.08	0.36
109	135	4.5	0.055	129	1860.69	0.05	167.46	0.10
98	258	4.5	0.071	129	5481.49	0.05	493.33	0.30
99	51	5	0.047	129	590.69	0.05	53.16	0.03
100	123	5	0.062	129	2313.89	0.35	208.25	0.88
19	220	5.5	0.137	129	16310.29	0.35	1467.93	6.22
110	180	5.5	0.124	129	11423.66	0.35	1028.13	4.36
101	88	4.5	0.164	129	7051.47	0.35	634.63	2.69
102	143	4.5	0.036	129	895.16	0.35	80.56	0.34

Table B.3. continued

Road Id	Length (m)	Width (m)	Slope	Rainfall (cm)	Ungraded Road (kg/yr)	Sediment Delivery	Cutslope (kg/yr)	Sediment (t/yr)
20	226	4.5	0.035	129	1335.54	1	120.20	1.46
21	213	4.5	0.02	129	276.52	1	24.89	0.30
22	220	4.5	0.062	129	3724.80	0.35	335.23	1.42
23	27	4.5	0.112	129	1195.04	0.35	107.55	0.46
24	94	4.5	0.01	129	-91.05	0.35	-8.19	-0.03
25	109	6	0.062	129	2460.63	1	221.46	2.68
26	132	6	0.094	129	5899.76	0.35	530.98	2.25
27	120	6	0.073	129	3559.05	1	320.31	3.88
28	139	6	0.087	129	5486.89	1	493.82	5.98
103	51	6	0.126	129	3620.37	0.35	325.83	1.38
29	79	6	0.146	129	7052.45	0.35	634.72	2.69
30	210	4.5	0.025	129	565.36	1	50.88	0.62
31	86	4.5	0.125	129	4522.04	0.05	406.98	0.25
32	85	4.5	0.042	129	719.34	1	64.74	0.78
33	92	4.5	0.039	129	675.29	1	60.78	0.74
34	54	4.5	0.036	129	338.03	1	30.42	0.37
35	83	4.5	0.034	129	461.82	1	41.56	0.50
36	64	4.5	0.061	129	1054.06	1	94.87	1.15
37	131	4.5	0.043	129	1158.85	1	104.30	1.26
38	92	5	0.104	129	4024.69	1	362.22	4.39
104	60	4.5	0.07	129	1245.14	1	112.06	1.36
39	127	4.5	0.038	129	885.85	1	79.73	0.97
40	103	4.5	0.034	129	573.10	0.05	51.58	0.03
41	98	4.5	0.01	129	-94.92	0.05	-8.54	-0.01
42	42	4.5	0.028	129	151.21	0.05	13.61	0.01
43	63	4.5	0.021	129	98.56	0.05	8.87	0.01
44	71	4.5	0.08	129	1834.94	0.05	165.14	0.10

Table B.3. continued

Road Id	Length (m)	Width (m)	Slope	Rainfall (cm)	Ungraded Road (kg/yr)	Sediment Delivery	Cutslope (kg/yr)	Sediment (t/yr)
45	18	4.5	0.058	129	271.96	0.05	24.48	0.01
46	56	4.5	0.096	129	1941.39	0.05	174.73	0.11
47	61	4.5	0.03	129	258.25	0.05	23.24	0.01
48	43	4.5	0.088	129	1296.69	0.35	116.70	0.49
49	55	4.5	0.083	129	1509.03	0.35	135.81	0.58
50	116	4.5	0.056	129	1649.63	0.05	148.47	0.09
51	100	4.5	0.01	129	-96.86	0.05	-8.72	-0.01
52	173	4.5	0.054	129	2309.33	0.05	207.84	0.13
53	133	4.5	0.014	129	-20.58	0.05	-1.85	0.00
54	70	4.5	0.045	129	673.84	0.05	60.65	0.04
55	211	4.5	0.017	129	113.85	0.05	10.25	0.01
56	52	4.5	0.01	129	-50.37	0.05	-4.53	0.00
57	113	4.5	0.068	129	2234.62	0.05	201.12	0.12
58	34	4.5	0.333	129	8024.89	0.05	722.24	0.44
59	19	4.5	0.059	129	295.62	0.05	26.61	0.02
60	39	4.5	0.106	129	1582.51	0.05	142.43	0.09
111	134	4.5	0.154	129	9743.86	0.05	876.95	0.53
61	194	4.5	0.146	129	12989.01	0.05	1169.01	0.71
62	96	4.5	0.021	129	150.19	0.05	13.52	0.01
63	31	4.5	0.08	129	801.17	1	72.11	0.87
64	280	4.5	0.032	129	1368.76	0.35	123.19	0.52
65	239	4.5	0.027	129	786.76	0.35	70.81	0.30
66	175	4.5	0.025	129	471.14	1	42.40	0.51
67	94	4.5	0.052	129	1174.29	0.35	105.69	0.45
68	153	4.5	0.06	129	2449.89	0.35	220.49	0.93
69	109	4.5	0.155	129	8005.65	0.35	720.51	3.05
112	234	4.5	0.01	129	-226.66	0.35	-20.40	-0.09

Table B.3. continued

Road Id	Length (m)	Width (m)	Slope	Rainfall (cm)	Ungraded Road (kg/yr)	Sediment Delivery	Cutslope (kg/yr)	Sediment (t/yr)
70	275	4.5	0.025	129	740.36	0.35	66.63	0.28
71	244	4.5	0.124	129	12669.88	1	1140.29	13.81
72	101	4.5	0.01	129	-97.83	0.35	-8.80	-0.04
73	80	4.5	0.025	129	215.38	0.35	19.38	0.08
74	24	4.5	0.036	129	150.24	0.05	13.52	0.01
75	240	4.5	0.071	129	5099.06	0.05	458.92	0.28
76	83	4.5	0.091	129	2641.44	1	237.73	2.88
113	185	5	0.039	129	1508.80	1	135.79	1.64
77	252	5	0.065	129	5134.28	1	462.09	5.60
105	147	6	0.086	129	5695.49	1	512.59	6.21
78	158	6	0.102	129	8042.90	0.05	723.86	0.44
79	59	4.5	0.06	129	944.73	0.05	85.03	0.05
80	238	4.5	0.069	129	4822.38	0.05	434.01	0.26
114	174	4.5	0.065	129	3190.59	0.05	287.15	0.17
81	106	4.5	0.016	129	31.88	0.05	2.87	0.00
82	103	4.5	0.031	129	469.51	0.05	42.26	0.03
83	75	4.5	0.01	129	-72.65	0.05	-6.54	0.00
84	151	4.5	0.199	129	16285.15	0.05	1465.66	0.89
85	204	4.5	0.059	129	3173.98	0.35	285.66	1.21
86	219	6	0.2	129	31734.36	0.35	2856.09	12.11
87	214	6	0.127	129	15380.06	1	1384.21	16.76
88	65	4.5	0.096	129	2253.40	1	202.81	2.46
89	117	4.5	0.046	129	1172.69	1	105.54	1.28
90	101	4.5	0.045	129	972.26	0.05	87.50	0.05

B.2 Summary of R commands used in statistical analysis

The first test performed on the model outputs was a Shapiro Wilks test of normality. Table B.4 summarizes the p-values associated with the Shapiro Wilks normality test. All p-values were less than the assigned alpha of 0.05, leading to the rejection of the assumption that the data followed a normal distribution.

Table B.4. Summary of p-values for the Shapiro Wilks Normality test conducted on sediment output from each road erosion prediction model.

Model	p-value of Shapiro Wilks Normality Test
SEDMODL	9 e-15
WEPP: Road	2 e-16
STJ-EROS	2 e-16

A summary of statistical code used in R is listed below.

Normality Test (alpha 0.05)

```
> shapiro.test(SEDMODL)
        Shapiro-Wilk normality test
data:  SEDMODL
W = 0.6658, p-value = 9.488e-15

> shapiro.test(WEPP)
        Shapiro-Wilk normality test
data:  WEPP
W = 0.581, p-value < 2.2e-16

> shapiro.test(STJEROS)
        Shapiro-Wilk normality test
data:  STJEROS
W = 0.532, p-value < 2.2e-16

> qqplot(SEDMODL,WEPP,xlab="SEDMODL",ylab="WEPP")
> qqplot(SEDMODL,STJEROS,xlab="SEDMODL",ylab="STJ-EROS")
> qqplot(WEPP,STJEROS,xlab="WEPP",ylab="STJ-EROS")
```

Equal Variance Test (alpha 0.05)

```
> y<-read.csv("output.csv")
> attach(y)
```

```
> names(y)
[1] "Yield"   "Group"   "Slope1"  "Method1" "Slope2"  "Method2"

> fligner.test(Yield,Group)
        Fligner-Killeen test of homogeneity of variances
data:  Yield and Group
Fligner-Killeen:med chi-squared = 46.4626, df = 2, p-value = 8.143e-11
```

The codes below represent the paired Wilcox test used to compare the model outputs for significant differences between means.

Paired Wilcox Test with Bonferonni fix (alpha 0.0167)

```
> wilcox.test(SEDMODL,WEPP,paired=TRUE)

        Wilcoxon signed rank test with continuity correction

data:  SEDMODL and WEPP
V = 3637, p-value = 0.3101
alternative hypothesis: true location shift is not equal to 0

> wilcox.test(SEDMODL,STJEROS,paired=TRUE)
        Wilcoxon signed rank test with continuity correction
data:  SEDMODL and STJEROS
V = 6346, p-value < 2.2e-16
alternative hypothesis: true location shift is not equal to 0

> wilcox.test(STJEROS,WEPP,paired=TRUE)
        Wilcoxon signed rank test with continuity correction
data:  STJEROS and WEPP
V = 1494, p-value = 4.625e-07
alternative hypothesis: true location shift is not equal to 0
```

Spearman Rank Correlation Test

```
> spearman(SEDMODL,WEPP)
        rho
-0.06118548
> spearman(SEDMODL,STJEROS)
       rho
0.03073652
> spearman(WEPP,STJEROS)
      rho
0.0072052
```

Appendix C. Sensitivity analysis of buffer characteristics in WEPP: Road

In performing a sensitivity analysis on WEPP: Road, the effect of changes in buffer slope (%) and buffer length (m) on sediment yield (kg/yr) was evaluated. The following baseline conditions were used initially: outsloped, rutted, native surface road with high traffic intensity, road gradient of 1%, road length and width of 50 m and 4.5 m respectively, fill slope of 0.1%, fill length of 50 m, 0% rock fragments, and clay loam soil type. Buffer lengths included 0.5, 50, 75, 100, 125, 150, 175, and 200 m. Buffer slopes included 0.1, 3, 6, and 9%. Figure C.1 illustrates the results of this initial trial.

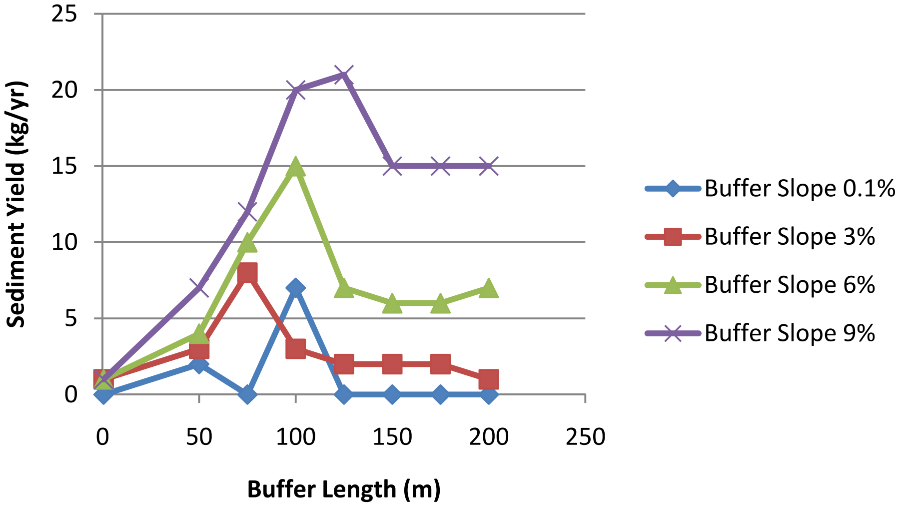

Figure C.1. Effect of buffer slope and buffer length on sediment yield (kg/yr) prediction using the WEPP: Road model (baseline conditions).

An additional four trials were performed to determine if the peak in sediment yield at a buffer length of approximately 100 m occurred if other factors were varied. Table C.1 describes the changes made in each of the four trials. Figures C.2-C.5 illustrate the effect of buffer slope and buffer length on sediment yield as factors are varied in each of the four additional trials.

Table. C.1. Description of four additional trials used to evaluate the effect of buffer slope (%) and buffer length (m) on sediment yield (kg/yr) prediction using WEPP: Road.

Trial Number	Soil Type	Fill Slope (%)	Traffic Intensity
1	Sandy Loam	0.1	High
2	Clay Loam	1	High
3	Sandy Loam	1	High
4	Clay Loam	2	Low

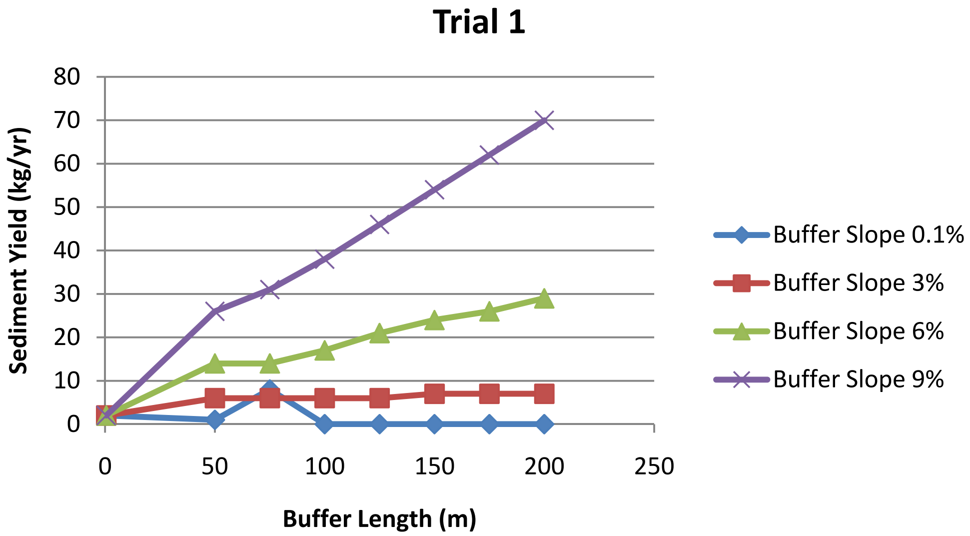

Figure C.2. The effect of buffer slope (%) and buffer length (m) on sediment yield (kg/yr) prediction using WEPP: Road. Factors adjustment includes a change from clay loam to sandy loam soil.

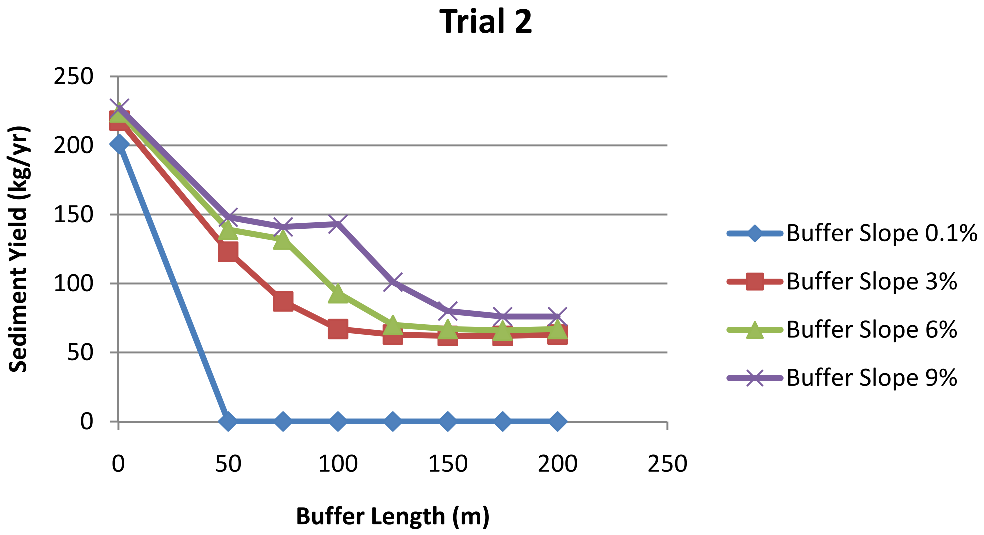

Figure C.3. The effect of buffer slope (%) and buffer length (m) on sediment yield (kg/yr) prediction using WEPP: Road. Factors adjustment includes a change from fill slope of 0.1% to 1%.

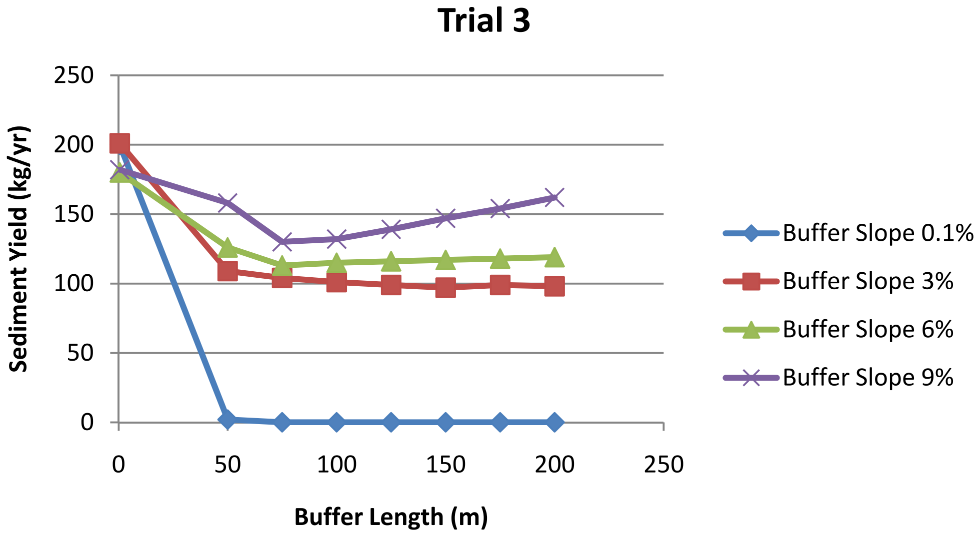

Figure C.4. The effect of buffer slope (%) and buffer length (m) on sediment yield (kg/yr) prediction using WEPP: Road. Factors adjustment includes a change from clay loam to sandy loam and fill slope of 0.1% to 1%.

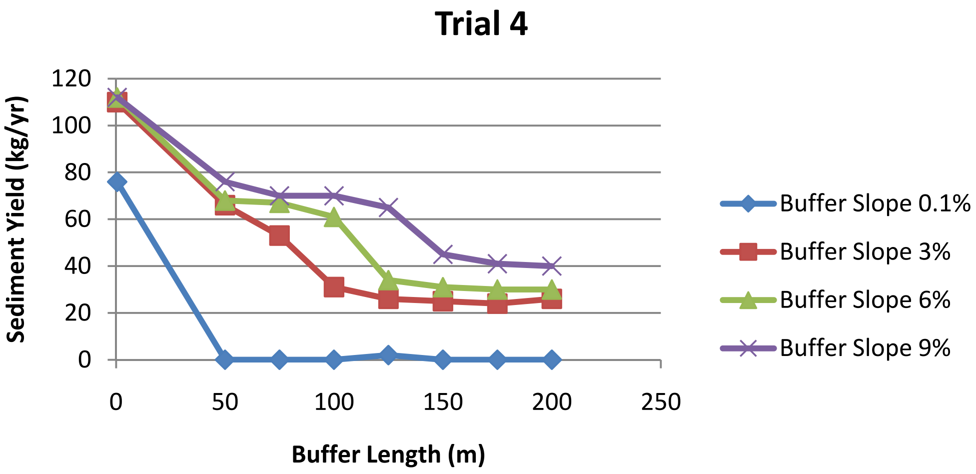

Figure C.5. The effect of buffer slope (%) and buffer length (m) on sediment yield (kg/yr) prediction using WEPP: Road. Factors adjustment includes a change from fill slope of 0.1% to 2% and traffic intensity from high to low.

As explained by Dr. Bill Elliot, one of the developers of WEPP: Road, these observations indicate erosion of the buffer (W. Elliot, personal communication, 25 June 2010). In climates with periods of heavy rain, the runoff generated by the road may cause erosion of the buffer. The amount of erosion that could occur depends on soil type and slope.