To the Graduate Council:

I am submitting herewith a dissertation written by Glenn Graham Hyman entitled "Sediment Transfer in the Rio Pacuare Watershed and Neighboring Basins in Costa Rica." I have examined the final copy of this dissertation for form and content and recommended that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Geography.

Carol P. Harden

Carol Harden, Major Professor

We have read this dissertation
and recommend its acceptance:

Sally P. Horn

Theodore H. Schmudde

G. Michael Clark

Accepted for the Council:

C. W. Minkel

Associate Vice Chancellor and
Dean of the Graduate School

SEDIMENT TRANSFER IN THE RIO PACUARE WATERSHED AND NEIGHBORING BASINS OF COSTA RICA.

A Thesis Presented for the Doctor of Philosophy Degree
The University of Tennessee, Knoxville

Glenn G. Hyman
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DEDICATION

This dissertation is dedicated to my father

Dr. Theodore Martin Hyman

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ABSTRACT

This study examines factors related to sediment yield, sediment source areas, and sediment transfer processes on the Atlantic slope of the Cordillera de Talamanca in Costa Rica. Data were gathered from existing sources and from the author's field observations to describe and analyze sediment transfer processes in steep, humid Costa Rica. First, a broad scale analysis of 18 watersheds was carried out to investigate general relationships between sediment yield and watershed physical factors. Then, a more detailed, field-based analysis and three sediment budget scenarios were developed for the 651 km^2 Pacuare River basin.

Globally, past research sets up the expectation that forested basins yield little sediment compared to agricultural basins. Land cover has commonly been cited as the determining factor in sediment yields in the tropics. Results of this study demonstrate that the expected relationship between land cover and sediment production is weakened by other controlling factors in the steep humid tropics of the Cordillera de Talamanca, where basins that have very little human intervention and are almost completely forested show high sediment yields. The influence of deforested lands on sediment transfer in the steep, humid area investigated in this study is not as important as is commonly suggested for tropical watersheds.

Although a detailed sediment budget could not be developed, an approximate accounting of sediment processes for the Río Pacuare watershed shows that surface wash erosion can only provide a small portion of the sediment that leaves the basin. Consistent with previous research stressing the importance of mass wasting in

basin denudation, this research shows that mass wasting processes contribute more than half the sediment exported from the Pacuare drainage basin. However, in contrast to previous emphasis on mass wasting's role in long-term basin denudation, this analysis indicates that landslides mobilize considerable quantities of sediment even over relatively short time spans. In the Talamanca region of Costa Rica, storms and earthquakes of sufficient magnitude to trigger sediment-producing landslides each have recurrence intervals of about five years, suggesting that in any given year there is about a 40 percent probability of an event that will trigger landslides.

TABLE OF CONTENTS

LIST OF TABLES

TABLE | PAGE

LIST OF FIGURES

FIGURE PAGE

LIST OF PLATES

1. INTRODUCTION

Sediment transfer is related to the flow of energy and water at the earth's surface, and to the susceptibility of the surface to resist the forces acting upon it. This relationship has been recognized by casual observers for centuries and has been a major focus of study by geomorphologists. Knowledge of the erosion-sediment discharge relationship is critical to understanding earth surface processes and landforms, and it enhances our ability to live in our environment. Sediment transfer is a natural process, occurring throughout the world, and is accelerated by almost every aspect of human use of natural resources. The major processes are known, but no model has been developed that can be applied to different watersheds in different regions. The complexity of sediment transfer systems, lack of knowledge of the wide range of Earth environments, and difficulties analyzing these systems at different spatial scales have hindered our progress in understanding the sediment transfer system. This research addresses some of these problems by exploring erosion and sediment yield in the steep humid tropics of Costa Rica, at different spatial scales and using several approaches.

Drainage basins in the steep humid tropics have received less attention than in other areas of the world, perhaps due to their comparatively low population densities and isolation. Yet the effects of human resource use in the steep humid tropics deserves greater attention in countries like Costa Rica where these lands are among the few available for future development. Maps showing the progression of deforestation in Costa Rica during this century make it clear that the steep and humid Cordillera de Talamanca is the last large area remaining undeveloped (Keogh 1984, Sader and Joyce 1988, Ministerio Del Medio Ambiente y Energía 1995). Under even conservative scenarios of the future of Costa Rican agriculture and economy, these undeveloped lands are likely to be exploited to support an increased future population (Hall and Hall 1993). In addition to human impacts, humid-tropical steeplands deserve close study for the exaggerated presence of perhaps the two most important physical factors in land surface change: high precipitation and steep slopes. The magnitudes of these factors are outside the range of values obtained in the great majority of soil erosion and sediment transfer investigations. When human impacts on the environment and natural processes are considered together, it is clear that humid-tropical steeplands merit careful geographic study.

Of particular concern in the steep humid tropics is the need to extend our knowledge of the erosion-sediment yield relationship, sediment transfer processes, and the interaction of humans with the environment. A first step towards addressing problems of sediment movement and resources is to obtain basic knowledge of the frequency, magnitude and geographic distribution of the principal processes. Based on these concerns, the following questions as applied to the steep, humid tropics of Costa Rica are addressed in this study:

1. What are the principal processes resulting in sediment transfer in drainage basins?
2. What is the role of land cover in sediment movement in watersheds?
3. What are the magnitude, frequency, and geographic distribution of sediment transfer in drainage basins?

1.1 Factors Controlling Sediment Yield

Previous studies have shown that it is unlikely any global relationship can be drawn between drainage basin sediment yield and the upstream controlling factors of sediment production (Wilson 1973, Dunne 1979, Jansson 1988). Many variables operate in a complex manner to define the sediment transport regime over all but the smallest watersheds. Even relationships drawn for a distinct region may not be applicable to areas with similar characteristics (Dunne 1979). As with soil erosion models, there is no satisfactory universal or regional model that explains sediment production and yield. Nevertheless, there have been many valuable attempts to develop such a model and much has been learned by investigating sediment production - sediment yield relationships.

The studies of Fournier (1949) and later Langbein and Schumm (1958) on the relationships between rainfall and sediment discharge set the stage for much of the recent research on the controlling factors of sediment yield in drainage basins. Both of these studies included plots of the relationship between mean annual precipitation and mean annual sediment yield (**Figure 1**). Where rainfall is extremely low, there is not enough runoff to entrain sediment. Sediment yields increase sharply in semi-arid environments where vegetation is sparse but there is sufficient runoff to entrain sediments. With increasing precipitation, sediment yields decrease due to the protective effect of vegetation. In humid environments, such as the eastern United States, where precipitation is not strongly seasonal, sediment yields are low compared to global data means. Langbein and Schumm's curve includes data to about 1,500 mm of rainfall, a point where Fournier's curve begins to rise, reflecting higher sediment

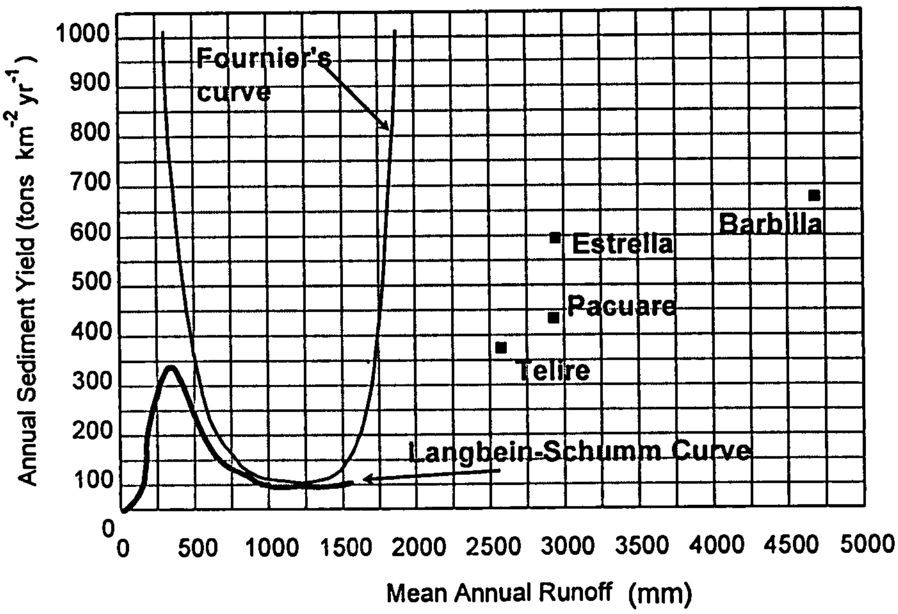

Figure 1. Relationship between mean annual sediment yield and mean annual runoff. Also plotted are four drainage basins in the Cordillera de Talamanca. Adapted from: Langbein, W. B. and S. A. Schumm. 1958. Yield of sediment in relation to mean annual precipitation. Transactions of the American Geophysical Union. 39:1076-1084 and Instituto Costarricense de Electricidad. 1993. Boletín No. 3. Sedimento en Suspensión. Oficina de Estudios Hidrológicos. San José.

yields in basins with a monsoon climate. Fournier argued that where precipitation has a seasonal character, sediment yields are high, as exemplified by basins in semi-arid and monsoon climates. In such regions, erosion rates are especially high after the dry season, when vegetation is sparse. Neither of these early studies, and very few subsequent studies, included basins with high rainfall and without a strong seasonal character such as the Costa Rican basins plotted in **Figure 1**. Jansson's (1988) survey of world rivers suggested that basins with annual runoff over 1,800 mm generally have high sediment yields, but research on the climate - sediment yield relationship in the humid tropics is lacking. While the early papers (Fournier 1949, Langbein and Schumm 1958) noted some interesting findings, they were equally important for the questions they raised that their research did not address. For example, what factors, in addition to climate, explain sediment yield? How do the processes work together and what are the relationships for areas they did not study? Later work began to consider the utility of a more detailed look at the controls on sediment production, one incorporating multivariate data (Anderson 1957, Gibbs 1967, Dunne 1979, Calvo 1991).

There came to be more focus on the sediment delivery ratio as a tool to move toward understanding hillslope erosion and its relationship to sediment yield at the watershed outlet (Maner 1958, Spraberry *et al.* 1960, Roehl 1962, Robinson 1977, Trimble 1974, Trimble 1975). The sediment delivery ratio is the ratio of sediment evacuated from a watershed to the gross erosion above the watershed outlet. High sediment delivery ratios indicate high sediment transport efficiency. Low values suggest sediment deposition within the watershed. Some studies (Roehl 1962, Trimble 1974, Trimble 1975, Trimble 1977) have shown that, for basins 25 km^2 or larger in North America, normally 20 percent or less of the sediments mobilized in a watershed leaves the basin. Watershed sediment discharge is not in equilibrium with upstream sediment mobilization in basins where human activities or earth surface processes have accelerated erosion (Trimble 1977).

A significant advance in the study of drainage basin sediment movement came about with the use of sediment budgets in studies of watershed dynamics (e.g., Kelsey 1980, Swanson *et al.* 1982, Trimble 1983, Duijsings 1987, Bordas and Walling 1988, Reid 1990, Kondalf and Matthews 1991, Sutherland

and Bryan 1991). A sediment budget is a quantitative accounting of sediment mobilization, storage, and evacuation in watersheds. The sediment budget technique, despite its many limitations and difficulty of application, led to a greater appreciation of the many processes involved in the movement of sediment from hillside to basin outlet. Compared to past research, more attention was paid to depositional processes and the time factor in sediment delivery (Trimble, 1977). The application of the budget concept also seems to have led to a much greater identification of what we do not know about sediment movement in drainage basins. This was clearly pointed out by Kondalf and Matthews (1991), who argued that care should be taken to report residual terms and uncertainties in the calculation of the sediment budget. Nevertheless, the sediment budget, much like the widely used water budget, is applicable to a wide range of geomorphological, engineering and environmental problems (Reid 1990).

Sediment budget studies in temperate climates indicated that the storage component should not be neglected. Trimble (1983), for example, showed that even though widespread soil conservation techniques were employed in the Coon Creek basin in Wisconsin, sediment yields continued to be high. He attributed this condition to remobilization of sediment stored in channels and flood plains. Basins with gentle slopes provide numerous storage opportunities for sediments making their way to the watershed outlet. When these basins experience accelerated soil erosion, an equivalent increase in sediment yield may not occur because sediment evacuation is limited by transport capacity of the river channels, not sediment supply to the system (Trimble 1983). In basins with steep slopes, fewer storage opportunities should result in higher sediment delivery ratios. Lehre (1981), working in a 1.7 km^2 mountainous watershed in California, U.S.A., found that 53 percent of mobilized sediment was delivered to the basin outlet in a three-year period. He estimated that storage is depleted by flow events with a recurrence interval of at least 10 to 15 years. Dietrich and Dunne (1978) estimated that, for a 16 km^2 basin in Oregon, half of the soil eroded from hillslopes is stored as colluvial or alluvial deposits. Given the well known relationship between basin area and sediment yield, such studies in small mountainous watersheds may not be representative of larger basins (Roehl 1962). Unfortunately, few watershed sediment budgets have been calculated in large basins, and fewer still in tropical environments.

1.2 Erosion and Sediment Yield in the Steep Humid Tropics.

The present study examines soil erosion and sediment dynamics in a steep humid-tropical area. The humid tropics, as discussed here, follow the definition of Lal (1983): those tropical regions where precipitation exceeds potential evapotranspiration for more than nine months during the year. No consensus exists for threshold slope angle to define "steep." For the geomorphologist, the defining slope angle value will depend on the purpose of a particular study. I chose a value of 10 degrees because it seems to be a reasonable lower limit for what can be considered "steep" for agricultural activities, an important factor in soil erosion.

Globally, two tropical areas broadly conform to areas of slopes greater than 10 degrees and with rainfall exceeding evapotranspiration at least nine months of the year: parts of Southeast Asia and steeplands in southern Central America and Colombia. The shaded areas in **Figure 2** -- areas receiving more than 1,500 mm of precipitation annually, where annual precipitation exceeds annual evapotranspiration by more than 1,000 mm, and relief exceeds 500 m -- show the approximate extent of the steep humid tropics. I made the map, intended to show steeplands with high rainfall, from the United Nations Environmental Program's GRID global data sets (Deichmann and Eklundh 1991). Smaller areas of steep humid tropics not shown on this map include some islands in the Pacific Ocean and the Caribbean. The Costa Rica study area for this research corresponds to this broad definition of the steep humid tropics.

Very few studies of soil erosion and sedimentation in humid-tropical steeplands have been carried out, but several reports of basin denudation in the tropics are notable. Although not conducted in the steep humid tropics, Dunne's (1979) study of 61 basins in Kenya is important for its findings and methodological approach. It is one of the few studies of soil erosion in the tropics that looks at several variables. Dunne found land use to be the single most important variable affecting sediment yields and noted the importance of roads as a sediment source. Undisturbed catchments had low sediment yields. Unfortunately, regression relationships for the Kenya basins can not be used for other areas. This limitation highlights the difficulty in predicting sediment yields for a region.

Several studies of erosion and denudation in the steep humid tropics come from mountainous areas in New Guinea (Ruxton 1967, Simonett 1967, Pickup 1984). Ruxton (1967) argued that vegetation density in rainforest has

Figure 2. The steep humid tropics. Areas with over 1,500 mm of annual precipitation, precipitation exceeding annual evapotranspiration by more than 1,000 mm, and relief is more than 500 meters. Map developed by the author from global data sets. Source data from: Deichmann, Uwe and Lars Eklundh. 1991. Global digital data sets for land degradation studies: a GIS approach. GRID Case Study Series No. 4; UNEP/GEMS and GRID; Nairobi, Kenya.

been exaggerated. Pickup (1984), in studies of large basins in New Guinea, concluded that the mountainous headwaters and reworked alluvial plains are the major sediment sources.

Many tropical erosion studies focus on the immediate effects of rainforest clearing (see Bruijnzeel 1990 for review, Malmer 1990, Nortcliff *et al.* 1990, Spencer *et al.* 1990, Douglas *et al.* 1992, Greer *et al.* 1995). These studies describe large increases in sediment loads during and immediately after clearing of tropical rainforest. They may not be representative of the effects of actual deforestation practices on sediment because they generally describe erosion after mechanized clear-cutting. Some authors have suggested that the powerful images of broad scale land clearing have confused the issue of the effect of deforestation on erosion (Hamilton 1983, Hamilton 1985, Bruijnzeel 1991). They argue that tropical deforestation is typically less intrusive than portrayed. Less attention has been given to the more common incremental clearing carried out by relatively poor farmers with limited technology.

Mass wasting processes are important agents of slope denudation in the steep humid tropics. Wentworth (1943) and later White (1949) described the importance of soil avalanches for slope evolution in Hawaii. White (1949) suggested a cycle of processes that later has been referred to as the land-slip erosion cycle (Young 1972). Weathering is relatively rapid in steep tropical regions. Soil profiles on steep slopes reach a thickness beyond which they become unstable. A triggering event, such as heavy rainfall or earthquake shaking, produces landslides. The weathered layer is delivered to the stream channel, exposing less weathered bedrock on the slope. The cycle begins again as vegetation stabilizes the slope, the bedrock weathers to regolith and soil horizonation develops.

Earthquake-induced landslides have been shown to be an important erosional factor in denudation in the steep humid tropics and elsewhere. Keefer (1994) documented the role of earthquake-induced landslides in environments all over the world. For many areas, calculated erosion rates from earthquake-induced landslides are greater than calculations from fluvial sediment discharge. Keefer estimated that, for New Guinea, Peru, and New Zealand, earthquake-induced landslide erosion accounts for between 20 and 65 percent of the long-term slope erosion. Pearce and Watson (1986), working in New Zealand, found that earthquake-induced landslides provide enough sediment to account for sediment output estimated over the range of return periods for these sediment-mobilizing events. Fifty to 75 percent of the sediments remained in the channel system 50 years after the landslide event. Pain and Bowler's (1973) studies in Papua New Guinea suggested that sediments generated by earthquake-triggered landslides account for 60 to 70 percent of total denudation over a 1,000 year period. They found that sediment generated by landslides was flushed out of watersheds within a two-year period. Similarly, Garwood (1979) suggested that landslides triggered by earthquakes in Panama are a major disturbance to tropical forests. The importance of landslides and their role in sediment dynamics in Costa Rica has not been studied before, but since the country is earthquake-prone, this factor could be particularly important.

The research mentioned above has enhanced in our understanding of the geomorphological processes in the tropics, but the quantity and breadth of studies on erosion processes in the tropical steeplands remain limited (Dunne and Dietrich 1982, El-Swaify 1990). One explanation for the lack of studies is that these environments are often inaccessible. Since they do not represent some of the more important agricultural regions, such as the temperate breadbasket regions or Asian rice growing environments, they have received considerably less attention. One broad objective of the present study is to address our lack of understanding of the sediment production - sediment yield relationship in tropical steeplands.

The specific objective of the study is to evaluate drainage basin sediment transfer in the Río Pacuare watershed and nearby basins in Costa Rica. What are the principal factors that are responsible for sediment yield in this area? What are the principal sediment sources? Where are the sediment source areas? What is the magnitude and frequency of sediment production? The study follows a line of investigation inspired by Langbein and Schumm's (1958) classic paper on the relationship between precipitation and sediment yield, multivariate investigations of sediment yield and upstream geomorphological processes and more recent sediment budget and field level studies.

1.3 Development of the Present Study and Methodology

I first visited the Río Pacuare watershed (**Plate 1**) in December 1988 as part of a physical geography field course. The present study was conceived during a subsequent field expedition in the Río Pacuare watershed in July, 1991. During these trips, I was struck by the variability of stream turbidity in tributary streams entering the main channel. But the seemingly dense green vegetation seen from a landscape perspective suggested that sediment sources must be upstream and out of view of the main channel. During a July 1991 expedition to the lower Pacuare watershed, I observed abundant landslides in the gorge section, but I noted a lack of these landslides in areas further away from the main stem of the river.

I made field observations during parts of 1993, 1994, and 1995. My early experience in this area was in the lower part of the watershed, partly because this part is the most accessible. The 17 river kilometers from Tres Equis to Siquirres are accessible by raft or kayak and my observations of the main stem of the Río Pacuare are made primarily from this stream reach. During the first year and a half, I visited the watershed by mountain bicycle. During the second year and a half, a field vehicle allowed greater access. I was able to make a single expedition to the upper watershed near the Río Simari. Nevertheless, much of the 651 km^2 watershed could not be accessed.

Most of the data reported in this study derives from routine monitoring carried out by the Costa Rican Electricity Institute (ICE for its Spanish acronym). ICE collects a wide range of environmental data. Usually its efforts are in some way related to hydropower development, and most of the data reported here are primarily hydrologic data for proposed hydropower projects in the Pacuare and Reventazón basins (Cervantes 1989, Cerdas 1991, Jansson and Rodriguez 1992, ICE 1993, ICE 1994, CAURA 1994). ICE built the Cachí hydropower facility in the upper Reventazón watershed in the 1980s. Another hydroelectric dam, the Angostura project, is under construction on the Reventazón river near Turrialba. ICE plans to begin constructing the Guayabo-Siquirres hydroelectric project after the year 2000. The project will include a dam downstream from Angostura on the Reventazón river and a dam at Dos Montañas on the Pacuare river. It will transfer water from the Reventazón to the Pacuare watershed to take advantage of greater fall height of the planned dam at Dos Montañas.

Most of the geographic data presented here were managed in a geographic information system (GIS). I used Landsat Thematic Mapper satellite images to characterize land cover. I built a digital elevation model (DEM) of the Pacuare watershed from the eight 1:50,000 topographic quadrangles published by the National Geographic Institute (Instituto Geografico Nacional or IGN in Spanish). I added digital map layers of roads, streams, settlements, and location of rain and river gages -- all georeferenced to the 1:50,000 topographic map series. Details on the construction of the data base are described in a separate report (Hyman and Saenz 1995).

As I began, studying sediment loads in the Pacuare basin from published data (ICE 1993), it seemed worthwhile to investigate sediment loads in nearby drainage basins where field work could not be carried out. It became apparent that a rapid appraisal of sediment load and controlling factors, using a multivariable approach similar to Dunne's (1979) Kenya study, might provide important information on the sediment transfer system with relatively little expenditure of research resources. Such a project would also yield information on basins near the Pacuare basin where, in some cases, more or better information was available. Another advantage of a multivariate study of the relationship between sediment yield and upstream controlling factors for nearby basins would be that the spatial scale would allow me to step back and take a broad look at the region in general. I proposed a broad-scale analysis covering 18 watersheds in steep humid-tropical Costa Rica where data were available or could be easily developed. The project was carried out in conjunction with colleagues at Centro Agronomico Tropical de Investigación y Ensenañza (CATIE) and is presented in Chapter 2.

This dissertation mainly deals with sediment transfer processes in the Río Pacuare watershed near Turrialba. Following a summary of the multvariate analysis in Chapter 2, I discuss the Río Pacuare Watershed study area and the local factors important for erosion and sediment transport in Chapter 3. In Chapters 4, 5 and 6, I present and discuss the results of my research on the three major processes of the sediment transfer system in the Pacuare area -- surface wash, mass wasting, and channel processes. In Chapter 4, I review the local literature on soil erosion and describe my field experiments on surface wash processes in the Pacuare basin. I discuss mass wasting processes in Chapter 5, based on my field observations, a review of local literature on the topic, and my analysis of remote sensing data. Chapter 6 is a discussion of channel processes and is based on data collected by ICE and on my own observations of the main stem of the Río Pacuare and its tributaries. I synthesize the observations presented in previous chapters in Chapter 7, discussing sediment transfer processes as they are related to each other and to the sediment transfer system in general. I discuss the geographic distribution of sediment source areas at the hillslope and watershed scale and the magnitude and frequency of different sediment transfer processes in the Pacuare and nearby drainage basins. I present the main conclusions of the study in Chapter 8, with some comments on the implications of the research and directions for future study.

2. MULTIVARIATE ANALYSIS OF STEEP HUMID-TROPICAL WATERSHEDS IN COSTA RICA

2.1. Introduction

As I began to look at the problem of the erosion-sediment yield relationship in the Río Pacuare drainage basin, it seemed reasonable to see what kind of information was available for nearby drainage basins, data that may be superior to the Pacuare data or could be used as a surrogate for inadequate data. ICE (1993) reports sediment yield data for drainage basins covering most of the national territory. The sediment yield data from Costa Rican basins raised several questions. What is occurring upstream of the sampling points in nearby basins that is related to their sediment loads? To what can be attributed the differences in sediment loads between different basins? What are the upstream controls on sediment yields? Since these questions were relevant to the original questions I had posed for the Pacuare basin, I decided to see what might be gained from undertaking a broad-scale study of the controls on sediment yields.

My approach to understand the controls on sediment dynamics in the Costa Rican drainage basins follows the methodology of Anderson (1957) and Dunne (1979). The approach was to search for relationships between sediment yield at the basin outlets and the biophysical characteristics of the upstream watersheds. Sediment yield depends on a variety of processes that, in combination, give a watershed its sediment transport regime. It can be expected that certain combinations of watershed land cover, relief, rainfall and other factors will be related to sediment load. A multivariate analysis indicates how well sediment yield can be predicted based on variables important in sedimentation processes (Anderson 1957). The analysis presented here gives a broad-scale view of sediment yield and factors important in sediment mobilization.

With the assistance of Sergio Velasquez, David Williams, and Ogden Rodas, colleagues at Centro Agronomico Tropical de Investigación y Enseñanza (CATIE), I conducted a broad-scale analysis of 18 watersheds in steep humid areas of Costa Rica to search for relationships between sediment yield and its controlling factors. In this chapter, I discuss the humid-tropical steeplands in Costa Rica, the rationale for selecting basins and variables, and the results of the multivariate statistical analysis. A preliminary assessment, based on a smaller set of observations and more approximate measures of watershed characteristics, was presented in a separate report by a member of our project team (Williams 1995). The data, results, and interpretations of that study are not comparable with results reported here because the data set is different. Nevertheless, I will discuss that report together with the results of my analysis.

2.2. The Steep Humid Tropics of Costa Rica

The steep humid tropics of Costa Rica include the mountain ranges of the Cordillera de Talamanca and the Cordillera Central (**Figure 3**). Costa Rica's unique blend of volcanic and seismic activity is related to its location at the "triple junction" of the Nazca, Cocos, and Caribbean tectonic plates (Anonymous 1992). The Cordillera de Talamanca in the southern half of the country is characterized by plutonic rocks that rose up beneath sedimentary layers (Castillo 1993). The highest parts of the Talamancas are composed of granites and

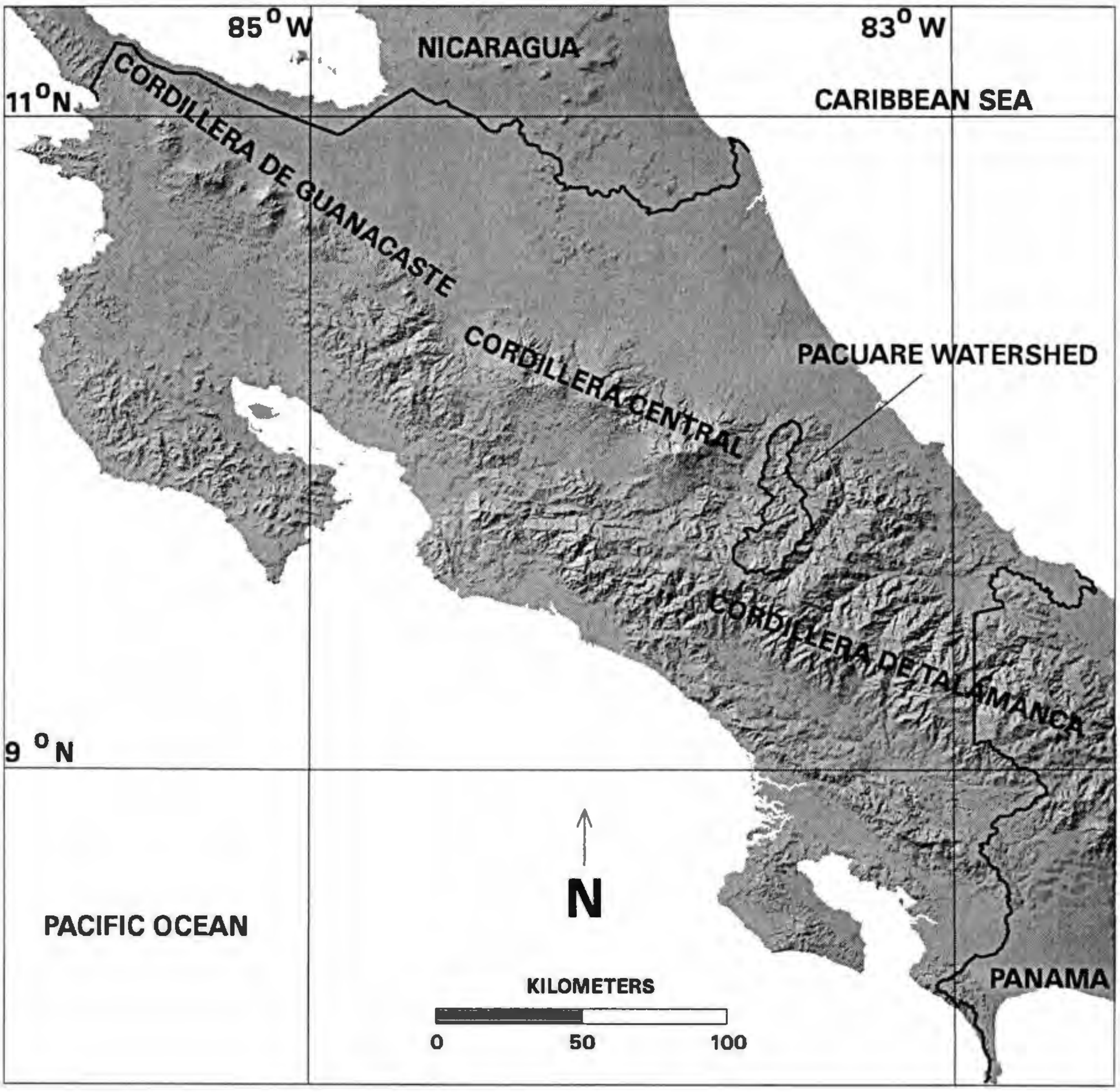

Figure 3. Shaded relief map of Costa Rica showing steeplands in the Cordillera Central and the Cordillera de Talamanca.

grandiorites interspersed with sedimentary rocks while the lower elevations include mostly sedimentary rocks and Neogene volcanic rocks. Further north lie the volcanic ranges of the Cordillera Central and the Cordillera de Guanacaste. These ranges are composed of Quaternary volcanos, some of which are presently active.

Costa Rica's climates are generally more humid on the lands draining to the Caribbean Sea and comparatively drier in areas west of the continental divide (Vargas 1994). The wet season normally extends from May to November, with a small decrease in precipitation during July and August, locally know as the "veranillo" or little summer. The dry season is most pronounced on the Pacific slope of mountain ranges. Although rainfall does diminish between December and April on the Caribbean slope, many areas still receive more than 100 mm of rainfall during these "dry" months.

Soils are diverse, reflecting the influence of volcanic activity and the variation in climate and topography. One will find typical tropical soils that are highly weathered and have a well developed structure (mostly ultisols), as well as other soils that reflect soil forming factors unique to the local environment, such as volcanic, colluvial, and alluvial soils. Soil maps of Costa Rica indicate that the Talamanca mountains are mostly comprised of ultisols (Perez and Alvarado 1978, Acon and Asociados 1989). Relative to other areas in Costa Rica, these soils are older, are more highly weathered and have higher clay content in the subsoil. Soils in the Central Cordillera are mapped primarily as inceptisols. Late Quaternary volcanic activity is the principal soil forming factor in the development of these inceptisols.

Land cover in the steep humid areas of Costa Rica is predominantly forest, but change is occurring rapidly (Keogh 1984, Sader and Joyce 1988, Ministerio del Medio Ambiente y Energía 1996). In the past, there has been greater land cover change pressure on the Cordillera Central due to its better soil for agriculture and proximity to the populated Central Valley. Presently, forested areas in the Central Valley and Cordillera Central largely coincide with legally protected areas. The Talamanca mountains contain one of the last large expanses of forest that has not been cleared for development and this area will likely be a focus for future agricultural expansion (Hall and Hall 1993).

One important aspect of the study area is that it includes some basins that have been cultivated for many years, some that are on the agricultural frontier, and others that are almost completely forested. In contrast to the Quaternary age volcanic landscapes of the Cordillera Central, where soils are more fertile, soil loss in the Talamanca area could have serious negative effects on soil productivity for agriculture. Because little is known about the watershed scale effects of land cover change in steep humid areas, more study is needed in this region, especially before massive land cover change occurs.

2.3 Selection of Watersheds and Variables

We selected drainage basins near the Río Pacuare watershed having sufficient data to be included in a statistical analysis. The watersheds and values for the variables included in the analysis are shown in **Figure 4** and **Table 1**. Of the 12 basins with their headwaters in the Cordillera de Talamanca, five drain to the Pacific Ocean and seven drain to the Caribbean Sea. Four basins drain the

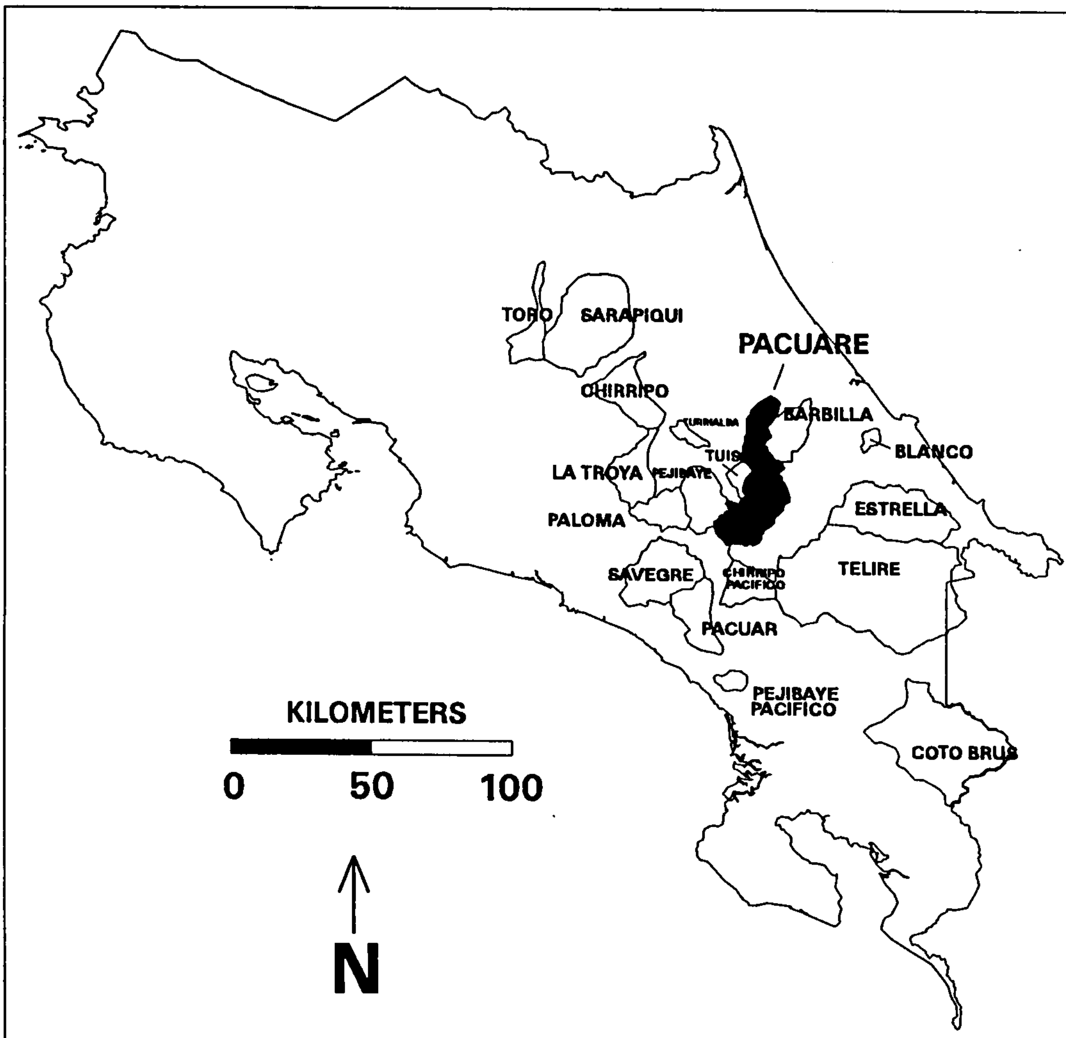

Figure 4. Location of 18 watersheds included in multivariate analysis.

Table 1. Biophysical, runoff, and sediment data for 18 Costa Rica drainage basins

BASIN NAME	ID	AREA	RELIEF	RMEAN	KMEAN	SMEAN	PERC	CMEAN	92RO	ROREC	SED92
Chirripó	16	376.3	3074	340	0.165	29	0.696	0.004	5178	5204	1812
Blanco	3	50.0	500	523	0.076	10	0.572	0.009	3409	2315	1191
Barbilla	4	212.0	1521	522	0.052	21	0.852	0.029	4743	3630	4412
La Troya	13	274.6	2237	204	0.160	15	0.117	0.115	728	927	184
Estrella	2	634.5	2163	433	0.068	20	0.721	0.138	2813	2048	4805
Savegre	29	473.0	3279	367	0.107	32	0.598	0.018	2282	2914	123
Pacuare	6	651.8	3012	343	0.074	24	0.721	0.021	2288	2845	478
Pejibaye Atlántico	10	226.9	1972	446	0.094	26	0.732	0.029	3456	4309	125
Telire	1	2120.5	3661	325	0.077	28	0.901	0.020	2564	2573	1253
Pacuar	30	322.7	1863	578	0.148	16	0.000	0.023	1471	2121	79
Turrialba	14	76.7	2403	254	0.145	19	0.038	0.116	1948	1710	284
Coto Brus	31	1133.3	2956	376	0.115	14	0.359	0.026	1497	2109	105
Paloma	11	371.1	2283	271	0.143	21	0.818	0.015	2459	2898	112
Upper Reventazón	18	820.9	2837	508	0.097	10	0.750	0.007	5024	4379	298
Toro	19	191.4	2539	407	0.119	18	0.462	0.037	3732	3888	174
Chirripó Pacífico	32	317.9	2938	302	0.136	33	0.673	0.055	1776	2222	67
Pejibaye Pacífico	33	128.0	798	522	0.155	12	0.000	0.013	703	1572	21
Tuis	15	49.3	1240	229	0.069	21	0.516	0.088	2348	2776	85

AREA - in square kilometers, from ICE 1993
RELIEF - in meters, calculated by author from Costa Rica Digital Elevation Model (1:200,000 scale source data)
RMEAN - USLE R factor averaged across basin (Varhson 1990)
KMEAN - USLE K factor averaged across basin - from FAO soil maps ACON y Asociados 1989, Perez y Alvarado 1978
SMEAN - slope angle in degrees averaged across basin - from Costa Rica Digital Elevation Model
PERC - percentage of basin in forest
CMEAN - USLE C factor averaged across basin - from 1992 MAG land cover map, using values (Derckson 1991)
92RO - 1992 runoff expressed in millimeters (ICE 1994)
ROREC - average annual runoff for the period of record expressed in millimeters
SED92 - sediment yield (tons km^{-2} yr^{-1}) from ICE 1993
SEDREC - average annual sediment yield over period of record, from ICE 1993

Central Volcanic Range to the Caribbean Sea. The upper Reventazón watershed (La Troya) has headwaters in both the Talamancas and the Central Volcanic Range. The Blanco watershed lies along a local highland area near the Caribbean coast. ICE established gaging station locations largely with a view to future water resources development projects. The watershed outlets defined by gaging station location are, in most cases, located above where the basins spill out onto less steep lands in the coastal plains or intermontane valleys. The following criteria were used to select the basins: (1) All are in mountainous areas. (2) They are in predominantly rural areas with forest, rangeland, and agricultural land uses. (3) They do not have a strong dry season, thus excluding basins in the Guanacaste region. (4) The basins flow unimpeded by dams and are without large hydrological diversion projects in their drainage areas. (5) Each basin defines a unique hydrological unit -- no watershed is up-valley from another in the study.

We selected independent variables based on their relation to sediment yield processes and on the availability of suitable data. Much of the data, developed at the CATIE GIS laboratory, were derived from the 1:200,000 scale series of maps produced by the Instituto Geografico Nacional (IGN). We digitized some of the data in connection with a separate project (Van Laake and Hyman, in review). We determined watershed boundaries and areas from these maps and later checked our results against the digital elevation model (DEM). The DEM was made from a triangular irregular network (TIN) interpolation of scanned contour lines. The resulting raster model has a spatial resolution of 200 m. Slope, relief and area characteristics for each watershed were derived from the

DEM.

Traditionally, multivariate studies of this type assign semi-quantitative values or percentages for each variable (Dunne 1979, Calvo 1991). For example, the percentage of a given land cover is one of the variables in many studies. The approach taken in this analysis was to use values from the Universal Soil Loss Equation (USLE) in addition to traditional measures because they should give a more reliable quantitative estimate of the variable (Wischmeier and Smith 1965). The USLE land cover factor C is derived empirically from plot studies (Wischmeier and Smith 1965). Averaging the USLE C factor across each basin allows inclusion of a measure of the effect of land cover for all the different cover types. We obtained a digital land cover map from a study based on 1992 aerial photographs (Ministerio de Medio Ambiente, 1996). The factor values were assigned to each land cover according to values derived from a previous study (Jeffrey *et al.* 1989, Derckson 1991). We also determined the percentage of each basin in forest to give us an extra variable in addition to the USLE C factor.

Rainfall intensity values (R factor in the USLE) were compiled from a study of erosivity for 115 rainfall measuring stations distributed throughout Costa Rica (Vahrson 1990) and are expressed in English units. Vahrson's (1990) table of R factors includes the latitude and longitude of each pluviograph station along with the rainfall erosivity value. I used these locations to generate a point map of the stations. I georeferenced the point map to the Lambert projection to standardize the R factor map to other data held in my GIS. I used TIN interpolation techniques to convert the point map to a continuous surface of rainfall intensity, expressed as the USLE R factor. I calculated the average R factor by summing the 200 m grid cells of the R factor data layer for each basin and then dividing by the total number of cells in the basin.

Soil erodibility data were based on a combination of two 1:200,000 scale soil maps. Most of the soil data is based on Acon and Asociado's (1989) soil association map. Because this map did not cover protected areas in Costa Rica, data for protected areas had to be inserted from an earlier soil map (Perez y Alvarado, 1978). To do this, I used a Boolean operation that determines if each grid cell is mapped in the 1989 soil map. If the grid cell was not mapped on the 1989 map, meaning it falls in a protected area such as a national park, I assigned the soil unit from the 1978 map to that grid cell. K values were assigned to grid cells using data for the representative soil type for each unit, applied to Wischmeier and Smith's (1965) equation:

$$100K = (2.1M^{1.14})(10^{-4})(12 - a) + 3.25(b - 2) + 2.5(c - 2)$$

where:

M = % silt and fine sand * (100 - % clay)
a = percent organic material
b = structure class
c = permeability class

Structure and permeability classes were assigned according to Wischmeier and Smith (1978).

Table 1 shows runoff reported as discharge (from ICE 1994) converted to millimeters of rainfall distributed over each basin. The table reports sediment yields in tons km^{-2} yr^{-1} for the year 1992 and the average annual sediment yield for the period of record (ICE 1993). ICE calculated the sediment yields based on the sediment rating curve technique. ICE hydrologists take a large number of water samples when gaging stations are established and thereafter take one or two samples per month. ICE determines sediment concentrations as the average in parts per million of three depth integrated samples distributed over the river cross section at each station. Concentrations are plotted against discharge on log-log paper and sediment loads calculated based on daily discharge.

2.4. Results

Stepwise multiple linear regression was carried out in search of relationships between the dependent variable (sediment yield) and the independent variables (runoff, mean slope, basin area, cover, soil erodibility, rainfall intensity and relief). The methodology follows that of Dunne (1979) and Calvo (1991). The linear additive model is structured as follows:

$$\begin{aligned} SSY = {} & \beta 0 + \beta 1AREA + \beta 2RELIEF + \beta 3RMEAN + \beta 4KMEAN + \\ & \beta 5SMEAN + \beta 6CMEAN + \beta 7ROREC \end{aligned}$$

where:

SSY92	=	1992 suspended sediment yield in tons km^{-2}
SSY	=	predicted mean annual suspended sediment yield in tons km^{-2} yr^{-1}
β0	=	intercept in tons km^{-2}
AREA	=	basin area in km^2
RELIEF	=	basin relief in m
RMEAN	=	USLE rainfall intensity factor R averaged across basin
KMEAN	=	USLE soil erodibility factor K averaged across basin
SMEAN	=	USLE slope steepness factor S averaged across basin
PERC	=	percentage of basin in forest
CMEAN	=	USLE land cover factor C averaged across basin
92RO	=	1992 runoff in mm
ROREC	=	average annual runoff in mm for each basin.

Table 2. Model results of multivariable analysis of relationships between sediment yield and controlling factors for 18 basins.

MODEL VARIABLES Independent	Dependent	R^2	Standard Error of the Estimate tons km^{-2} yr^{-1}
1,2,3,4,5,7,8	SED92	0.68	1055
8	SED92	0.19	2642
7,8	SED92	0.38	2626
3,7,8	SED92	0.51	2480
1,3,7,8	SED92	0.58	2271
1,3,5,7,8	SED92	0.62	2104
9	SEDREC	0.17	615
5,9	SEDREC	0.19	453
1,5,9	SEDREC	0.19	375
1,5,7,9	SEDREC	0.2	327
1,3,5,7,9	SEDREC	0.2	293
1,3,5,7	SED92	0.41	1920

1 - AREA - in square kilometers, from ICE 1993
2 - RELIEF - in meters, calculated by author from Costa Rica Digital Elevation Model (1:200,000 scale source data)
3 - RMEAN - USLE R factor averaged across basin (Varhson 1990)
4 - KMEAN - USLE K factor averaged across basin - from FAO soil maps ACON y Asociados 1989, Perez y Alvarado 1978
5 - SMEAN - slope angle in degrees averaged across basin - from Costa Rica Digital Elevation Model
6 - PERC - percentage of basin in forest
7 - CMEAN - USLE C factor averaged across basin - from 1992 MAG land cover map, using values (Derckson 1991)
8 - 92RO - 1992 runoff expressed in millimeters (ICE 1994)
9 - ROREC - average annual runoff for the period of record expressed in millimeters
SED92 - sediment yield (tons km^{-2} yr^{-1}) from ICE 1993
SEDREC - average annual sediment yield from ICE 1993

I developed models from data for the both the period of record and for the 1992 hydrologic year. Various models were tested in search of relationships (**Table 2**). In some cases, the variables are not independent of each other. The best model, using runoff and sediment yield data for 1992, includes most of the variables and gave an R^2 of .68. I used CMEAN instead of PERC (percentage forest) because it was more closely correlated with sediment yield. The inclusion of relief and slope variables in the same model gave better results, but these variables are more highly correlated than the others. When relief or slope was excluded from the model, R^2 is less and the standard error of the estimate is greater. For the best model, the standard error of the estimate was 1059 tons

km^{-2} yr^{-1}, higher than the mean sediment yield of all basins.

The high error terms indicate that a clear relationship between suspended sediment yield and upstream controlling factors could not be established. These results show that variables traditionally used in multivariate analyses of watersheds do not permit the prediction of sediment yield in the Costa Rica drainage basins. Statistical relationships might improve by grouping the basins geographically. However, the results would not be statistically significant because the number of observations approaches the number of independent variables. Clearly, the low number of drainage basins in the database limits the statistical analysis.

Nevertheless, the lack of relationships is instructive because it suggests that some variables are not as important as might be expected. **Figure 5** shows runoff plotted against sediment yield for the 18 basins for (a) the 1992 hydrologic year and for (b) the period of record. The numbers next to each data point represent the average USLE cover factor for each basin, higher numbers indicating land covers more susceptible to erosion and lower numbers indicating land covers with less bare ground. The 1992 data show some positive relationship between sediment yield and runoff. The pattern for the period of record is less clear. A geographical grouping of the basins is evident. In very general terms, the seven basins draining the Talamancas to the Caribbean Sea have high runoff and high sediment yield. Those basins draining the Central Cordillera and the Talamancas to the Pacific have lower runoff and sediment yield despite greater agricultural intensity. For the three basins with more than 4,000 mm of runoff during the 1992 hydrologic year, cover factors are relatively

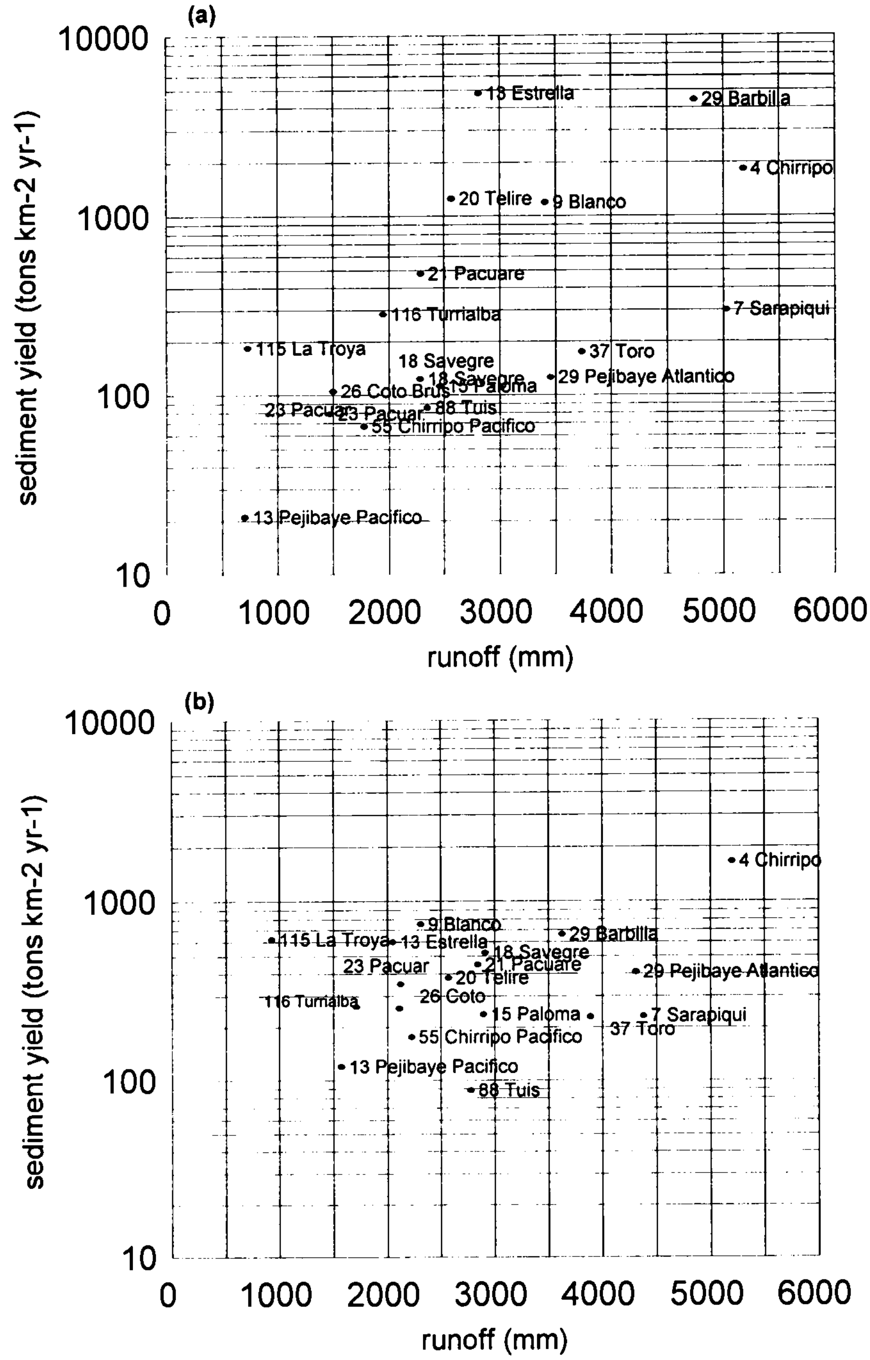

Figure 5. Sediment yield - runoff relationship for 18 Costa Rica drainage basins. (a) data for the 1991-1992 hydrological year. (b) data for the period of record of each individual station. Source data from: Instituto Costarricense de Electricidad. 1993. Boletín No. 3. Sedimento en Suspensión. Oficina de Estudios Hidrológicos. San José.

low and sediment yields are in the top half of the group. With this level of runoff, the expected protective effect of forest land cover appears to be less important. There may be a precipitation threshold above which sediment yields are high, regardless of land cover and other factors. The data indicate that considerable sheet, gully, and rill erosion occurs in the forest, that landslides are contributing great quantities of sediment, or that some other sediment transfer process is occurring.

While rainfall, slope and relief factors could indirectly reflect the importance of landslides, there is no variable in the data set directly representing mass wasting processes. The case of the Chirripó basin (not to be confused with Chirripó Atlántico draining the Cordillera de Talamanca) demonstrates this point. The basin, on the northern slope of Irazú volcano, has the highest average annual sediment load and the lowest cover factor of the basins studied. If land cover is the most important factor in sediment yield, we would expect basins with low cover factors (basins mostly in forest) to have low sediment yields. Unmapped landslides in the headwaters of the Río Chirripó watershed, contributing great quantities of sediments to the channel system, explain this contradiction (Hernandez 1991). There is a serious scale problem here. Landslides are rarely detected with the 1:200,000 scale source data. Although landslide areas are small or cannot be detected with 1:200,000 scale land cover data, the volume of landslide-caused slope erosion is potentially large due to the depth of material landslides move downslope.

Williams (1995), in a preliminary report, found similar results when looking at fewer basins and a less detailed data set. One observation from his report, confirmed here, is that there appears to be a grouping of the basins in similar geographic areas according to runoff and sediment yield. This grouping apparently reflects the greater precipitation and runoff on the Atlantic slope of Costa Rican mountain ranges (**Figure 5**).

The multivariate analysis presented here is subject to several limitations. The USLE R factor expresses annual rainfall intensities over the period of record but not individual events. The factor may offer insights about storms of high intensity, but could indicate little about storms of long duration that generate saturation overland flow. The soil erodibility factors are questionable because of the many difficulties of characterizing soil physical properties at such small scale. USLE values have not been calibrated to local conditions.

Although the quality of the sediment data is not fully known, problems with the sediment rating curve technique are well known (Walling and Webb 1981, Walling and Webb 1982, Walling 1983, Ferguson 1986, Walling 1988, Lemke 1991). ICE has long recognized the need to better represent the higher range of discharges (Picado 1993). In the Reventazón watershed, the use of daily discharges for sediment yield calculations has been shown to underestimate sediment loads by much as 25 percent when compared to hourly data (Jansson and Rodriguez 1992).

2.5 Conclusions from Broad-Scale Multivariate Analysis

The results of this analysis point to the insignificance of some factors traditionally thought to be the most important for sediment yield and to insufficiencies in the data set. Although land cover is normally an important factor in sediment production and forest cover is usually associated with low erosion rates, some forested basins in Costa Rica have comparatively high sediment loads. In contrast to Dunne's (1979) work, which derived some statistical relationships for Kenya, this analysis suggested that our current level of information on Costa Rica drainage basins does not permit prediction of sediment yields based on common environmental variables. That the three-dimensional nature of mass wasting processes could not be modeled at this scale is probably an important reason for the lack of clear relationships. The lack of sufficient data on earthquakes and their impact on generating landslides is another deficiency in the analysis. It is clear that watershed dynamics in the steep humid tropics of Costa Rica are complex and are difficult to understand using traditional models.

Any future multivariate analysis such as the one described above should include knowledge of the magnitude, frequency and spatial distribution of mass wasting phenomena. Projects underway to develop a digital topographic database at the 1:50,000 scale will allow greater resolution for slope parameters. Detailed analysis of rainfall events that increase sediment in streams is also needed. Efforts should be made to improve the sediment yield data. Perhaps most critical, land cover needs to be mapped in enough detail to reveal the surface conditions important for sediment transfer. However, it may be that modeling areas in the steep humid tropics as large as that of the 18 basins reported here is not feasible. The following chapters focus on sediment transport processes at a finer scale of resolution to explore local reasons for the lack of relationships in the analysis of the 18 watersheds.

3. THE PACUARE RIVER BASIN

3.1 Introduction

The principal focus of this research is the Río Pacuare watershed on the Caribbean slope of the Cordillera de Talamanca in Costa Rica. The multivariate analysis of steep humid-tropical watersheds presented in Chapter 2 suggested the possibility that some factors not captured in the analysis are affecting watershed sediment yields. There may be complexities in the local environment that common environmental variables do not reflect. In this and the following chapters the spatial scale narrows and a more detailed view of the steep humid tropics of Costa Rica is considered. Here, I describe the Río Pacuare watershed, particularly focusing on environmental factors important in sediment mobilization in the watershed.

The mountainous portion of the Río Pacuare basin, upstream from the Dos Montañas gaging station and extending to the highlands of the Cordillera de Talamanca, is considered in this study. **Plate 1** shows the location of the watershed boundary, the major stream channels, roads, trails, rain gages, and the two stream gaging stations operated by ICE. Many of the source topographic maps are 20 to 30 years old, so the current road and trail network may be 10 to 20 percent more dense. Roads and trails not mapped are small and serve farms in the watershed. The network shown here includes all the major roads and trails. The only paved road in the basin skirts the watershed divide between the Pacuare and the Reventazón river to the west. This road was the principal highway between the port city of Limón and the capital of San José up until the late 1980s. The other most heavily traveled road divides the basin between its upper and lower parts. It runs along a low pass near Tayutic (900 m elevation), down to the main stem of the river at Bajo Pacuare (at 590 m elevation) and then up the other side near Moravia (1,172 m elevation).

The population living within the basin is difficult to estimate but may be between 10,000 and 15,000 inhabitants. The largest settlement is Tayutic in the middle part of the basin with a 1984 population of 3,129 persons (CAURA 1994). Most people live along the western watershed divide between Tayutic and Linda Vista. Their farms extend from the western watershed divide down to the main stem of the Pacuare river. In the areas between Tres Equis and south to Tayutic, most farms are owned by families and are relatively small. Coffee and sugar cane cultivation is typical in farms of this area. Some large farms dedicated to sugar cane cultivation are near Tayutic. North of Tres Equis, farms are large, have absentee owners and are populated by local campesinos. Indigenous people are concentrated along the main stream channel upstream of the Bajo Pacuare gaging station and along the eastern watershed divide near the Finca Mirador rain gage.

3.2. Climate

High annual rainfall without a strong dry season is the dominant climatic characteristic of the Pacuare basin. Calvo (1986) classified climate for the neighboring Río Macho basin into five seasons that appear to conform well to climate observations in the Pacuare basin. A weak dry season occurs between January and May under the influence of the Bermuda high pressure cell. The first wet season occurs from mid-May through June, as the Intertropical

Convergence Zone (ITCZ) moves north. A "season of alternating wet and dry periods" extends from June to August. The second wet season occurs between August and October as the ITCZ shifts south again. Finally, a storm season occurs in November and December as a result of the influence of cold northern winds.

Table 3 shows basic climate data for the nearby CATIE weather station, 5 km to the west of the Pacuare watershed divide. Variations in temperature and evapotranspiration are small throughout the year and are influenced by the effect of clouds that trap radiation. Precipitation exceeds evapotranspiration except for a brief period in March (**Figure 6**). Between July and December, precipitation remains greater than evapotranspiration by at least 150 mm.

Precipitation patterns in the Pacuare can be separated into four zones that exhibit distinct behaviors. This view is based on incomplete information, given the low density of rainfall gages and strong variations in rainfall across short distances. The basis for the following description is my analysis of data provided by ICE and the rainfall intensity studies of Vahrson (1990) and Vahrson and Dercksen (1990). The location of rain gages is shown in **Plate 1. Table 4** shows annual rainfall and rainfall intensity at stations within the basin or on the watershed divide. **Figure 7** shows the geographic distribution of annual rainfall and the monthly distribution of rainfall for stations in the Pacuare basin. I made the map by the inverse distance weighted interpolation technique (see Burrough 1986 for review of technique), using the average annual rainfall for 18 weather stations in the Pacuare and surrounding areas. The four precipitation zones are described as follows:

Table 3. Climate data for the CATIE weather station near Turrialba

Climate Data: Costa Rica — Station: CATIE
Elevation : 602 meters — Location: 09°38' N 83°38' `W

Month	Max. Temp °C	Min. Temp °C	Relative Humidity %	Wind Speed km $hour^{-1}$	Sunshine hours day^{-1}	Solar Radiation MJ m^{-2} day^{-1}	Evapotranspiration (Penman) mm	Precipitation mm
January	25.7	16.4	87.2	2.5	4.7	16.0	75.0	171
February	26.1	16.4	86.0	2.5	5.0	17.8	77.0	127
March	26.9	17.0	84.9	3.3	5.3	19.4	96.0	86
April	27.3	17.9	85.5	2.5	5.1	18.7	94.0	122
May	28.0	18.7	87.4	2.2	4.7	18.5	92.0	226
June	27.8	18.9	88.9	2.2	4.2	16.7	82.0	281
July	27.2	18.6	89.5	2.2	3.7	15.6	79.0	277
August	27.5	18.5	89.0	2.2	4.1	16.8	85.0	253
September	27.8	18.5	88.5	2.2	4.5	17.8	86.0	249
October	27.5	18.4	88.9	2.2	4.7	17.5	86.0	246
November	26.6	18.2	89.5	2.2	4.3	15.4	72.0	263
December	25.9	17.1	88.8	2.5	4.1	14.6	70.0	310
Year					1642.5		994	2611
Average	27.0	17.9	87.8	2.4	4.5	17.1	82.8	217.6

Temperature:	1959-1994	36 years
Precipitation:	1942-1994	53 years
Solar Radiation:	1965-1994	30 years
Sunshine:	1959-1992	34 years

Source: Francisco Jimenez O. , Agrometeorologist - CATIE - Turrialba, Costa Rica - 1995

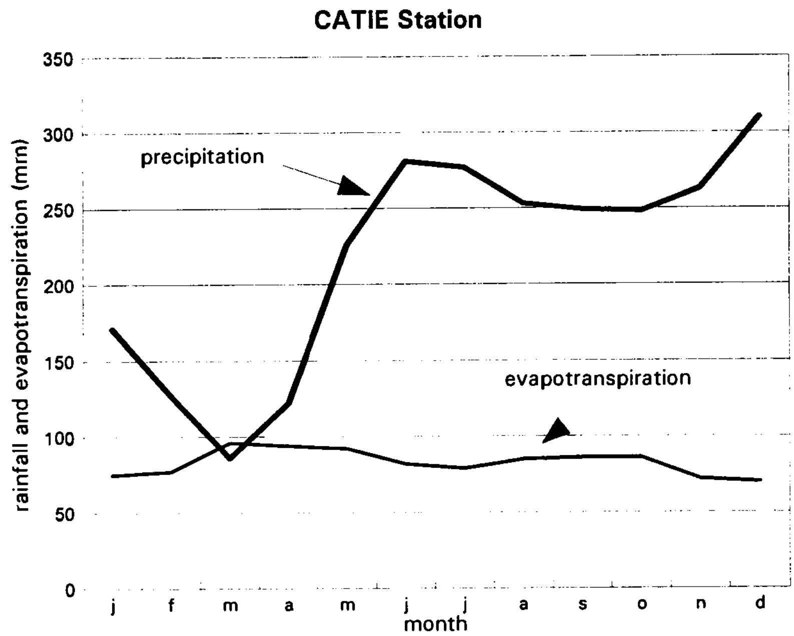

Figure 6. Precipitation and Evaporation at the CATIE weather station. Data provided by Dr. Francisco Jimenez - CATIE.

Table 4. Rainfall intensities in the Pacuare watershed

ICE Gage Number	Station	Average annual rainfall (mm)*	Elevation (masl)	Maximum Rainfall Intensity** 5 min	10 min	15 min	30 min	60 min
75002	Siquirres	3518	70	186	146	137	121	92
75003	Platanillo	2672	889	229	145	122	88	61
75004	Pacuare	2684	800	130	94	80	61	42
75005	Pacuar	3074	710	207	124	117	91	74
75007	Rocas Blancas	2899	825	235	159	141	108	73
75008	Cuencas	4742	1835	196	141	121	100	66
75022	Finca Mirador	4075	440	243	192	178	121	86

*Average annual rainfall - calculated by ICE

**from Vahrson and Dercksen 1990, reported as 10 year return period maximum rainfall intensities in millimeters per hour, for periods of 5, 10, 15, 30 and 60 minutes. For each station, at least 10 year data were analyzed. The authors did not report the period of analysis for the stations.

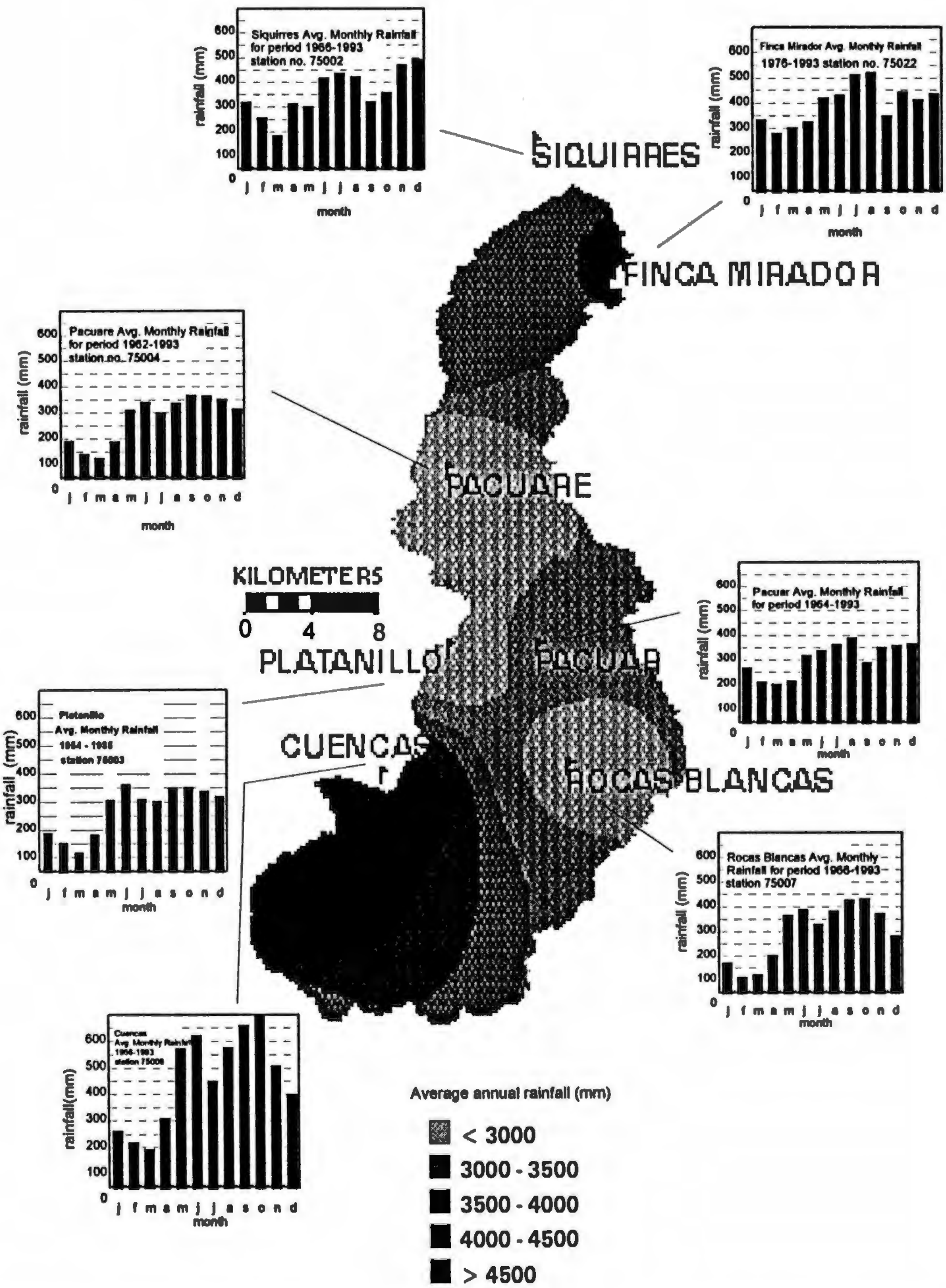

Figure 7. Rainfall distribution in the Pacuare basin. The map is an interpolation of average annual rainfall for 18 weather stations in the area. ICE provided the source data.

(1) The watershed north of Tres Equis near the watershed outlet. This area is greatly influenced by its proximity to the Caribbean Sea and the effects of northeast trade winds. Annual rainfall as measured at the Siquirres and Finca Mirador stations is about 4000 mm. This part of the basin receives some of highest rainfall amounts and the strongest rainfall intensities (Vahrson 1990, Vahrson and Derckson 1990). Since the lower watershed is where the mountains begin to rise above the coastal plain, weather systems from the north could be creating an orographic effect in this area. Rainfall during the months of September and October shows a distinct dip, characteristic of the Caribbean coastal plain pattern at Limón where October is the driest month.

(2) The middle part of the basin south of Tres Equis extending to all but the highest parts of the watershed and excluding the area near the Cuencas rainfall gage. Here, October is one of the wettest months. The dry season between January and March is stronger than in other parts of the basin. The region receives less rainfall than the northern and southwestern parts of the watershed. The Pacuare rain gage (ICE gage no. 75004) records the lowest rainfall intensities. The lower annual precipitation and rainfall intensity in the middle part of the basin suggests that this area is a transition zone between orographic highs in the southwestern and northern parts of the basin. The effects of these adjacent areas do not extend to this part of the basin.

(3) A zone along the upper western portion of the watershed. The highest rainfall totals (see the Cuencas station no 75008, **Figure 7**) occur in this zone.

There is an apparent channeling of winds along northwest trending mountain ranges that creates an orographic effect and accounts for the high rainfall (Ramirez *et al.* 1992). However, rainfall intensities are considerably less than those found in the northern part of the basin.

(4) A narrow zone extending from the Rocas Blancas rain gage to the southern-most edge of the watershed. Less is known about this zone due to its inaccessibility and lack of a rain gage. ICE's (CAURA 1994) isoline precipitation map indicates lower precipitation here. The zone is probably influenced by its proximity to the continental divide and weather systems originating in the Pacific Ocean. Average annual rainfall at the Villa Mills rain gage near the continental divide is 2,804 mm and this area has some of the least intense rainfalls in all of Costa Rica (Vahrson and Derckson 1990).

Annual precipitation and the average rainfall intensity in the Pacuare watershed is highly variable across the basin, which may be important for mobilization of sediments. The lower watershed in the northernmost sector of the area receives comparatively high amounts of annual precipitation and has the highest rainfall intensities. Total rainfall is greatest near the southwest watershed divide, but rainfall intensity there is low. The middle part of the basin receives the least rainfall and the least intense rainfall.

3.3. Geology

The geology of the Pacuare basin is complex and has varying influences on the potential for sediment mobilization. Some geologic formations are more susceptible than others to the development of dense drainage networks. Steep slope angles, important because of their gravitational potential to erode soil, appear to be better developed on certain rock types compared to others. Some geological features have unique characteristics important to sediment transfer. The following description of geological conditions for the Pacuare river basin is based on the work of Weyl (1957), Fernandez (1987), Cervantes y Soto (1988), Cervantes (1988), Cervantes (1989), Cerdas (1991), Chacón (1993), Castillo (1993), and my own field observations. **Figure 8** shows a map of geological formations compiled by ICE with the 1:50,000 scale river network superimposed. The map is part of an on-going geological survey by ICE geologists and is as yet unpublished (Cervantes 1993). Geological mapping has been concentrated in potential areas of hydropower development. The upper part of the watershed (showing drainage only) has only been mapped at the 1:200,000 scale (Sandoval *et al.* 1982).

Many of the rocks found in this area were formed in the Limón basin, a back arc basin extending from the Panama border to southern Nicaragua on the Atlantic coast of Costa Rica. Six spatially extensive geological formations and several minor ones as mapped by geologists at ICE are present in the Pacuare watershed. The Tuis formation is the most extensive unit in the watershed. It consists of Eocene sandstones and shales and is interspersed with volcanic brecchias. The Senosri formation contains well-cemented limestones and shales.

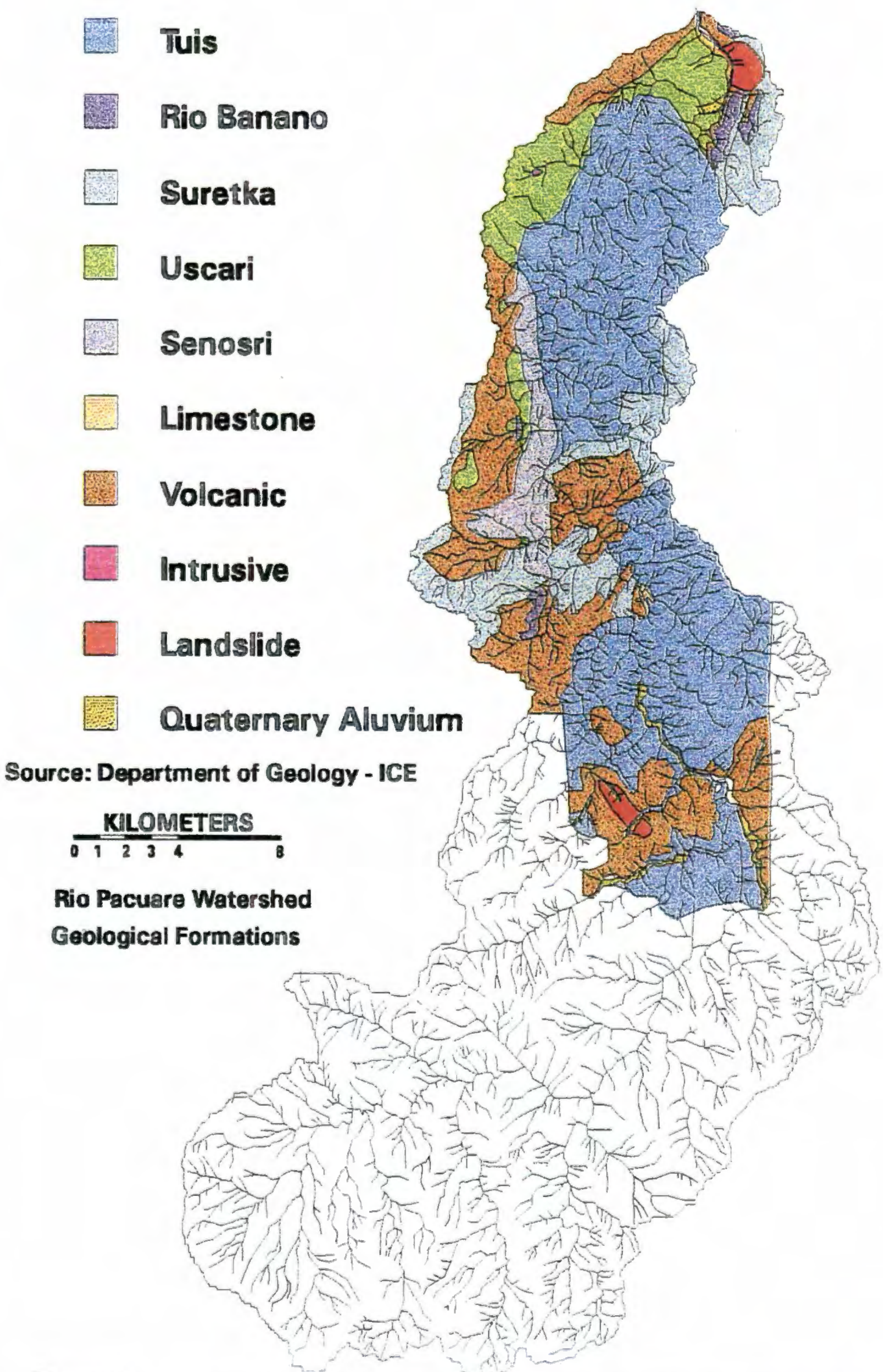

Figure 8. Geology of the lower Pacuare watershed with superimposed 1:50,000 scale drainage network. Map provided by Francisco Cervantes, ICE Geología.

The Uscari formation principally consists of shale and is interspersed in some places with limestones and calcareous sandstones. The Río Banano unit, found in the northernmost part of the basin, is composed of sandstones and shales rich in fossils. The Suretka formation is composed of conglomerates of basalt and andesite and is moderately weathered.

The Volcanic formation, composed of lavas and andesites, is present along the western edge of the watershed and is variable in its characteristics. In some places, the formation is indicated by surface deposits similar to the lahar flows near Turrialba, the Río General valley, and other parts of Costa Rica described by Kesel (1973). Other parts of this formation are characterized by tall dome-like structures such as those seen along the Turrialba-Siquirres road. Bergoeing and Malavassi (1982) mapped a Neogene volcanic crater near Pacayitas. Another area that could be a Neogene crater is in the upper watershed of the Río Platanillo near Cerro Silencio. Topographic maps indicate that this feature is very similar to the Pacayitas and Moravia craters. A third potential Neogene crater has been suggested for the middle part of the basin on the eastern side of the watershed (Garcia 1995). However this feature has not been verified in the field. The possible craters are difficult to identify because the features have been heavily weathered, but one study has suggested craters are common in the Cordillera de Talamanca (Alvarado 1984).

Several other minor units are mapped in the basin. Cervantes (1989) mapped Quaternary alluvium along the main stem of the Pacuare, even though it is limited in extent. Geologists have mapped a small limestone outcrop in the middle part of the basin. Cerdas (1991) mapped and studied quite extensively a

Holocene landslide unit near the basin outlet at Dos Montañas.

The upper part of the basin, mapped only at the 1:200,000 scale (Sandoval *et al.* 1982) is characterized by the sedimentary rocks previously described and plutonic rocks that form the backbone of the Cordillera de Talamanca. The Tuis formation comprises roughly 70 percent of the upper basin. The remaining 30 percent of the upper basin is composed of granite and grandiorites.

The geologic structure of the basin has several direct and indirect influences on the potential for sediment mobilization. Some formations are less cohesive and are thus more susceptible to mass wasting. Indirect influences include the impact of the parent material on soil formation and erodibility, and how the geologic strata influence the development of topography. The more extensive formations described above were ranked according to resistance to weathering and erosion by an ICE geologist (Cerdas 1995, Saenz 1995). Five groups were identified and are shown in **Table 5**. Drainage densities, as an indicator of geologic erosion, confirm the ranking of the top three in the list (**Table 6, Figure 8**). Clearly the drainage density of the Tuis formation is greater than that of the Volcanic and Senosri formations. However, the drainage density as a measure of denudation does not conform to Cerdas' ranking of geological resistance to erosion for the Uscari, Río Banano, and Suretka group. The Uscari formation has been described as particularly susceptible to mass wasting (Chacón 1993). In general, areas corresponding to the volcanic formation, due to its cohesive structure and resistant lithology, are the least susceptible to geologic erosion.

Table 5. Geological resistance to erosion of Pacuare watershed geological formations

Geological resistance to erosion	Geological formation
most resistant	Volcanic, Intrusive
	Senosri
	Tuis
	Uscari, Rio Banano, Suretka
least resistant	Landslide, Quaternary Alluvium

Source: Cerdas, Alexis. 1995. Personal Communication. Insitituto Costariccense de Electrida Turrialba, Costa Rica. October 25.

Table 6. Drainage Density Classified by Geologic Formation

Formation	Lithology	Stream* Length km	Formation** Area km^2	Drainage Density $km\ km^{-2}$
Volcanic	lavas, andesite	171.3	69.1	2.5
Senosri	carbonate	37.6	13.3	2.8
Tuis	limestone, sandston	431.9	134.1	3.2
Uscari	shale	49.2	24.1	2.0
Rio Banan	sandstone, shale	8.9	3.6	2.4
Suretka	conglomerate	82.6	34.3	2.4

*Stream lengths measured by the author from 1:50,000 scale topographic maps.
**Areas for geological formations measured by the author from ICE Dept. of Geology maps. Only areas mapped from the 1:50,000 scale are included.

3.4. Topography

The Pacuare basin is steeply dissected, with high drainage densities and very few gently sloping areas (**Figure 9**). Elevations range from 3,170 m above sea level (m.a.s.l) in the high Talamancas to 100 m.a.s.l at Dos Montañas, the watershed outlet. I calculated an average slope angle of 22 degrees from a digital elevation model. The surface area of the watershed, accounting for slopes, is 721 km^2 compared to 651 km^2 planimetric area. The slope map (**Figure 9c**) shows steep slopes are found throughout the elevation range, a point further supported by a weak positive correlation of 0.11 for slope angle and elevation. Gentle slopes coincide with the stream channel, some narrow flood plains, and some volcanic landscapes near the northwestern watershed divide. Some of the steepest slopes are found on hillsides along the river gorges of the northern part of the watershed. Another concentration of steep slopes is seen in the middle part of the basin at the eastern-most edge. A third concentration occurs in the highest headwaters of the basin.

3.5. Soils

The following description of soils for the Pacuare basin is based on 1992 and 1978 maps at the 1:200,000 scale (Perez y Alvarado 1978, Acon y Asociados 1989), a 1:50,000 scale study of potential soil use (Centro Científico Tropical 1993), an analysis of soils in the adjacent Tuis basin (Nuñez 1986) and my own field observations. My field observations suggested four broad-scale divisions of the spatial pattern of soils can be made for the study area:

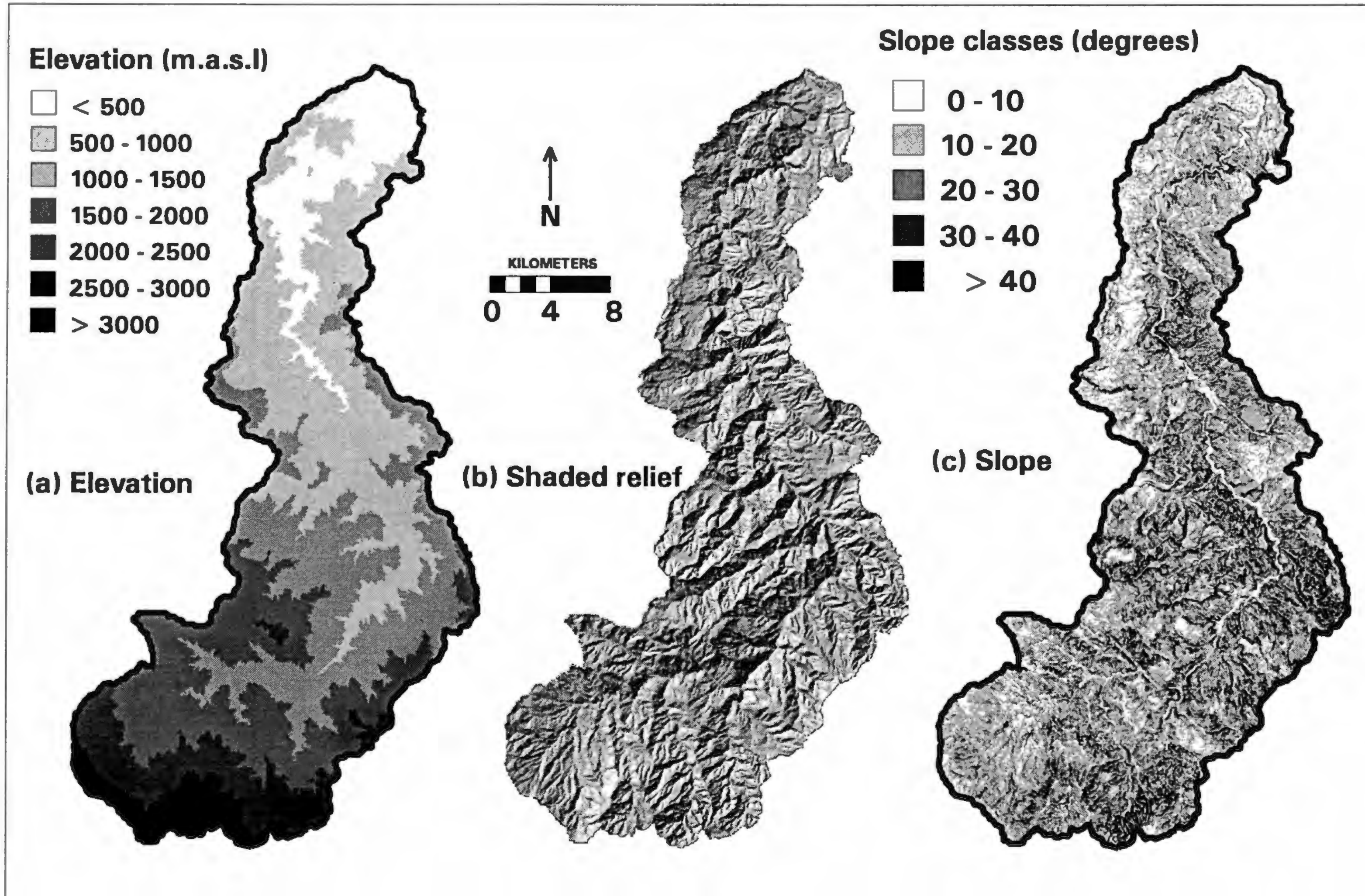

Figure 9. Topography of the Río Pacuare watershed. (a) elevation, (b) shaded relief, (c) slope.

(1) Residual soils overlying sedimentary and plutonic rocks on interfluves and ridgetops. These soils are developed on steep terrain, well drained, high in organic matter content, and relatively thin. On steep side slopes, soil profiles are about 1 to 2 m thick. On ridgetops, soil thicknesses reach 1.5 to 3 m. These soils generally correspond with areas that are forested. They have variable surface conditions, with some areas displaying bare soil and others largely covered by a thin layer of organic litter. Many of these soils were affected by small-magnitude colluvial processes and tend to have many rock fragments within the soil matrix. In general, they coincide with the Tuis, Suretka, and Río Banano geological formations.

(2) Soils on the volcanic lithologic units on the western portion of the middle part of the basin. These soils often correspond to areas of coffee cultivation or pastures. They tend to be reddish in color and have relatively greater development of clay subsoil horizons. Slope angles for these soils are generally less than those for the residual soils previously mentioned. Many of these soils are developed on ancient lahar or landslide deposits similar to those described by Kesel (1973). In pastures and coffee fields, large volcanic boulders often lie within a matrix of well weathered clays.

(3) Colluvial soils at the base of steep slopes and adjacent to low order stream channels. These soils result mostly from large landslides. They are found where the landslide deposit is in an environment favorable to stabilization. The soils develop a distinctive A horizon influenced by vegetation at the surface. Below the A horizon, soil particles are poorly sorted and there are numerous rock fragments. These soils are distributed throughout the watershed but their overall extent is not great.

(4) Alluvial soils on narrow floodplains and terrace remnants. These are young sandy soils developed in terrace and floodplain environments. They are layered with sand sized units and rounded cobbles that reflect reworking of sediments as the river migrates across the narrow valley floor. These soils occur in much less than one percent of the watershed.

The lack of a soil survey of the Pacuare basin prevents a detailed analysis of the spatial distribution of soil erodibility. These tropical soils are highly weathered and their textures probably do not vary greatly with parent material. Land cover may be a useful indicator of erodibility because soil organic matter, which largely depends on vegetation cover, is important in these soils. High organic matter content binds soil particles together, making them less susceptible to entrainment by flowing water. Thickness of the A horizon cannot be used as an indicator of erosion because depths vary greatly from one place to another.

3.6. Land Cover

Forest, pasture, sugar cane and coffee are the principal land covers in the Pacuare watershed (**Figure 10 and Table 7**). I based this land cover map on data

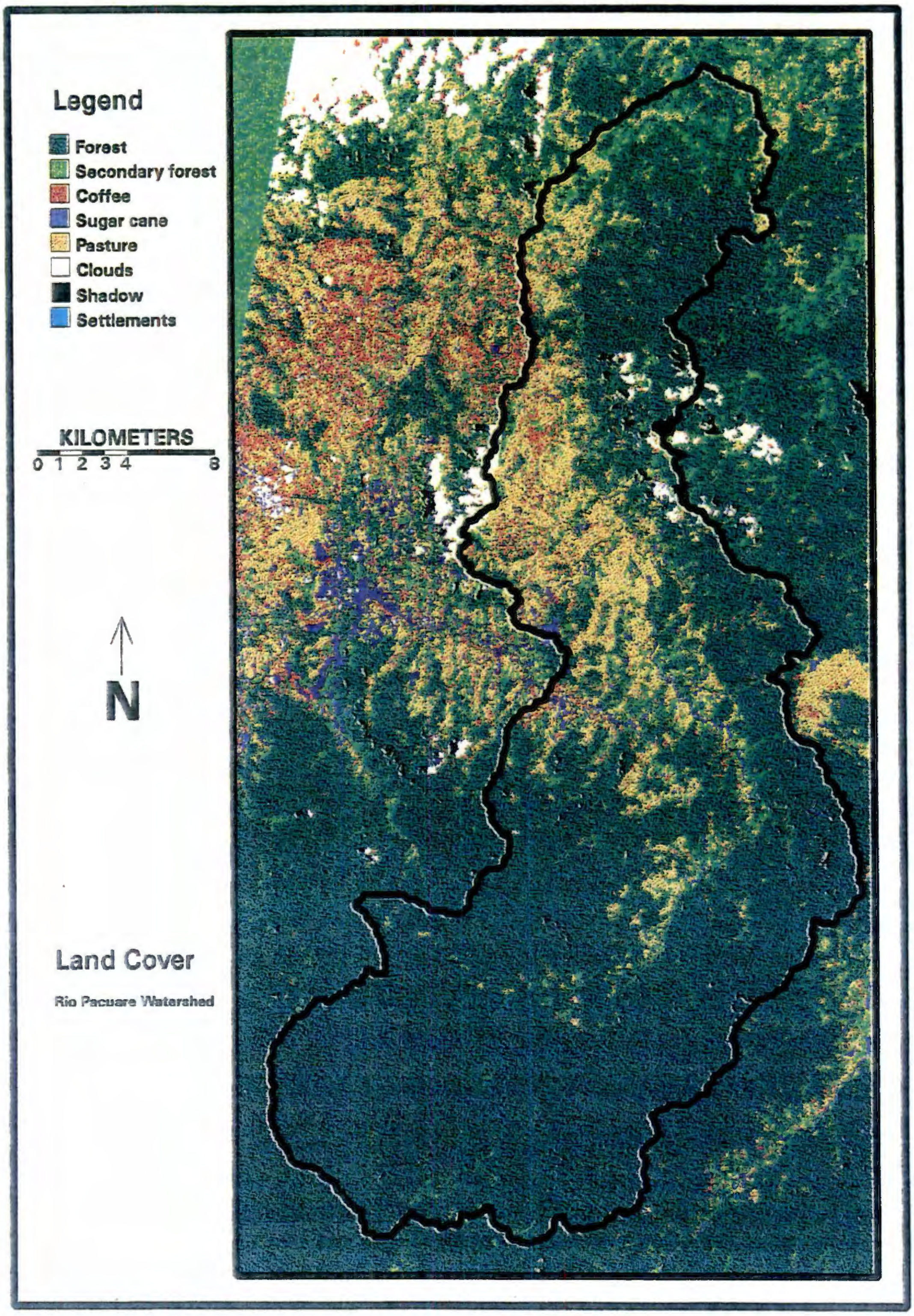

Figure 10. Land cover in the Río Pacuare watershed. Derived by the author from 1992 and 1990 satellite imagery.

Table 7. Land Cover in the Rio Pacuare Watershed

Cover Class	Area km^2	%
Forest	448.1	68.8
Secondary Forest	84.1	12.9
Coffee	30.0	4.6
Sugar Cane	14.5	2.2
Pasture	64.6	9.9
Clouds	4.7	0.7
Shadow	5.6	0.9

from two Landsat Thematic Mapper satellite images captured in 1990 and 1992 (**Figure 10**). I used a differential global positioning system (GPS) to map points for georeferencing and supervised classification of the satellite image. Most of the basin is mapped from the 1992 image. I used the 1990 satellite image to map areas with cloud cover in the 1992 image. Unfortunately, 1.6 percent of the watershed had clouds or cloud shadows in both images. A quantitative accuracy assessment was not carried out due to the difficulties of accessing the watershed. Nevertheless, when compared with existing data and aerial photographs, the classification shows much greater accuracy than existing maps (CAURA 1994, Saenz 1995) and can be considered a reasonable depiction of the 1992 land cover conditions.

Most of the Pacuare watershed remains forested (**Table 7 and Figure 10**). Almost the entire upper watershed above (to the south of) Bajo Pacuare is forested with exceptions including some riparian areas near the upper basin outlet. Forested areas of the lower basin are found mostly on the right bank of the main stem of the Pacuare river. The left bank of the Pacuare in the northern part of the basin has experienced more human disturbance than any other part of the basin. The pattern of secondary forest corresponds to proximity to human development and is concentrated in the lower part of the watershed. Some areas are also classified as secondary forest in the uppermost section of the basin, but could not be accessed to confirm their status. Because the pattern of secondary forest is not uniform, it is unlikely that these areas have been cleared by humans and more probable that the forest has been affected by natural disturbances. Land where rainforest has been cleared largely corresponds with accessibility as has been shown in tropical deforestation studies.

Land in crop cultivation comprises about seven percent of the watershed or 45 km^2. The coffee growing areas are between the Siquirres-Turrialba road and the main stem of the Pacuare. Sugar cane cultivation is concentrated along the road between Tuis and the bridge at Bajo Pacuare. The main concentration of sugar cane fields is at the town of Tayutic where gentle slopes are favorable to cultivation.

Pasture lands make up almost 10 percent or 65 km^2 of the watershed. Pastures are concentrated along the left bank of the Pacuare river between Bajo Pacuare and Linda Vista. They are found on a range of slope angles. Very few gently sloping lands remain where expansion of pastures could proceed. In some places, pastures are developed at ridgetops where there is some gently sloping land. Cerro Mirador is a case in point. Ranchers herd their cattle up steep rainforest trails to reach these highland pastures. At Cerro Mirador, cattle graze these highlands for a week and then are returned to pastures in low lying areas.

The pattern of land cover shown in **Figure 10** indicates that the Pacuare region is on the agricultural frontier. Several studies of land cover change in Costa Rica show how development is spreading eastward into the Cordillera de Talamanca (Keogh 1984, Ministerio del Medio Ambiente 1996). The region exhibits a striking combination of increased human activity and a suite of environmental factors related to sediment transfer found in very few environments. In the following chapters, I discuss some aspects of this combination of human and physical factors related to sediment transfer in the Pacuare region.

4. THE RIO PACUARE DRAINAGE BASIN: SURFACE WASH PROCESSES

4.1 Introduction

In Chapter 2, an analysis of some broad scale factors in sediment production showed that variables traditionally associated with land erosion do not explain sediment yield in basins of steep humid Costa Rica. I speculated that the lack of relationships could be due to an incomplete or inaccurate data set, or processes occurring at the basin scale that are not detected at the broader scale of the 18 watersheds in the analysis. In this chapter and the two that follow, I present an analysis of a finer geographic resolution, focusing on the Pacuare basin in particular, but including data for neighboring areas. My field observations suggested surface wash, mass wasting, and channel processes as the three major components of the sediment transfer system in the Pacuare basin. Therefore, I discuss these three components, beginning with this chapter, which focuses on surface wash erosion.

Surface wash is defined as sub-aerial erosion by water. It includes splash, sheet, rill, and gully erosion. It is distinguished from mass wasting by its comparatively slower instantaneous rate of sediment transfer. The discussion begins with a review of local literature on soil erosion. Although the record of erosion studies in Costa Rica is short, previous research indicates some general principles of erosion processes in the area. Next, I discuss my field level experiments and observations on surface wash erosion processes in the Pacuare basin.

4.2. Review of Soil Erosion Research in the Steep Humid Tropics of Costa Rica

Soil erosion plot studies and erosion risk modeling have been carried out for many years in Costa Rica, although synthesis of the results or broad consensus on the nature and effects of soil erosion has not emerged. However, it is possible to recognize some trends and general principles of soil erosion in Costa Rica, knowledge important to our understanding of the magnitude, frequency, and geographic distribution of sediment transfer processes. The following review considers soil erosion studies in steep humid areas of Costa Rica. This is not an exhaustive review of soil erosion research in Costa Rica, but is a selection of studies carried out in environments similar to the Pacuare basin. Some studies are probably not included as there tends to be a great deal of "gray literature" relative to published work. Plot studies are reviewed in greater detail since they are based on actual field measurements.

The universal soil loss equation (USLE) has been used in Costa Rica more than any other method for predicting soil erosion, despite a consensus that it is not correct to apply it outside of the temperate, low-relief, North American conditions for which it was developed (Roose 1977, Wischmeier 1986). Nevertheless, Jeffrey *et al.* (1989) predicted soil erosion rates in Costa Rica based on the USLE. Their map suggests that the Central Valley, Guanacaste, the Nicoya peninsula, and more generally along the Pacific slope are the areas where most soil erosion occurs, and that the forested Talamancas and Caribbean slope experience comparatively less erosion. With respect to sustainable agriculture, they concluded that 75 percent of the country has tolerable erosion rates (less than 10 tons ha^{-1} yr^{-1}) and 22 percent of the country has rates between 10 and

50 tons ha^{-1} yr^{-1}. They estimate rates greater than 50 tons ha^{-1} yr^{-1} for three percent of the national territory. Their method predicts very low erosion in all the forested areas of Costa Rica.

I. Mora (1987) used the USLE to predict soil erosion in the Pejibaye basin, a watershed adjacent to the Pacuare basin. Her results predict huge erosion losses, ranging up to 1,575 tons ha^{-1} yr^{-1}, and seem to be influenced heavily by the rainfall factors in a basin that receives some of the highest rainfall in Costa Rica. However, the maximum rates she predicts would result in surface lowering of up to 10 cm annually, rates clearly not occurring in this environment. Mora's (1987) results and those of others indicate that the USLE method overestimates soil loss rates in Costa Rica (Vahrson 1993).

Vahrson y Cervantes (1991a) compared measured erosion rates with those predicted using the USLE and found that the model overestimates soil erosion by an order of magnitude. They attribute the differences to lack of long term data for their plot studies and slope conditions outside of the range for which the model was produced. It seems likely that the generally higher rainfall intensities in the tropics could partly explain the overestimation of the model as well (Varhson 1990). United States researchers determined the soil erodibility factor from soils very different from those normally found in the tropics. And since relatively little empirical research has been conducted for crops like banana, sugar cane and coffee, the application of land cover factors to the model is uncertain. While USLE factors may be comparable for a single variable, it is not known if the relative importance of USLE variables is the same in Costa Rica as in areas in which the model was developed.

Mora (1991) used an index to map erosion susceptibility in the Reventazón watershed based on geological characteristics, drainage density, relief, and field observations. His map shows high susceptibility to erosion along watershed divides, near the volcanic peaks, and where human occupance has been intense. In a country-wide review of slope instability, Mora (1985) mapped several different kinds of mass wasting phenomena. His 1985 study suggested relatively sparse erosional activity in the Rio Pacuare and the Cordillera de Talamanca area.

Plot measurement studies of soil erosion in Costa Rica are relatively rare and, unlike most soil erosion research in the United States, are not standardized. Although many studies used plot areas equivalent to that of the USLE standard plot, few plots conformed to the standard nine percent slope. Cultivation takes place on slopes considerably steeper than nine percent in many parts of Costa Rica. **Table 8** shows results of plot studies of soil erosion in Costa Rica representing over 54 plot years of research. The short length of the studies is unfortunate and suggests that caution should be exercised when interpreting the results. Many of the studies were part of research programs at Center for Research and Training in Tropical Agriculture (CATIE), the University of Costa Rica (UCR), and the National University (UNA). The studies can be separated into three groups: those carried out in the middle Reventazón watershed in conjunction with CATIE, the studies in Puriscal by UNA researchers, and a single study on the slopes of the Irazú volcano north of Cartago.

The CATIE studies were carried out near Turrialba. Ives (1951) completed the first known and most detailed soil erosion plot experiments in

Table 8. Soil erosion plot studies in the steep humid tropics of Costa Rica

Source	location	crop	slope	plot period (months)	erosion rate (tons km^{-2} yr^{-1})	exceptional events* (tons km^{-2})	Bubnoff units**
Ives 1951	CATIE	various crops	16%	36	2.67	10097	2
Ives 1951	CATIE	grass	16%	36	0.00	0	0
Ives 1951	CATIE	bare soil	16%	36	8.00	12500	6
Ives 1951	CATIE	various crops	16%	36	79.33	7810	61
Ives 1951	CATIE	various crops	45%	36	274.33	8460	211
Ives 1951	CATIE	grass	45%	36	0.00	0	0
Ives 1951	CATIE	bare soil	45%	36	626.33	13100	482
Ives 1951	CATIE	various crops	45%	36	413.67	11090	318
Ives 1951	CATIE	sugar cane	45% +/-	36	0.00	0.00	0
Ives 1951	CATIE	maize	45% +/-	36	0.00	0.00	0
Ives 1951	CATIE	maize	45% +/-	36	0.00	0.00	0
Ives 1951	CATIE	maize	45% +/-	36	0.00	0.00	0
Ives 1951	CATIE	maize	45% +/-	36	0.00	0.00	0
Rocha 77	Bajo San Lucas	beans (weeded)	40%	12	172.00		132
Rocha 77	Bajo San Lucas	beans (mulched)	40%	12	22.00		17
Rocha 77	Bajo San Lucas	beans (mulched)	40%	12	27.00		21
Bermudez 1980	Turrialba "Florencia Sur"	coffee	30%	6	73.00		56
Bermudez 1980	Turrialba "Florencia Sur"	coffee with poro	30%	6	11.00		8
Bermudez 1980	Turrialba "Florencia Sur"	coffee with poro and laurel	30%	6	20.00		15
Berru 1980	La Suiza	pasture	42-51%	6	269.00		207
Romero 91	La Suiza "La Selva"	beans	69%	6	5720.00	2860.00	4400
Romero 91	La Suiza "La Selva"	bare soil	58%	6	5800.00	2900.00	4462
Garzon 1991	San Juan Sur	maize	15-35%	12	120.00		92
Faustino et al 1994	San Juan Sur	beans/maize	35%	12	1.10		1
Faustino et al 1994	San Juan Sur	beans/maize	25%	12	69.00		53
LeBeuf 1993	San Juan Sur	bare soil	25%	12	0.08		0
Vahrson and Cervantes 1991	Puriscal	coffee	56-59%	12	18.00		14
Vahrson and Cervantes 1991	Puriscal	coffee w/ shade	56-59%	12	150.00		115
Vahrson and Cervantes 1991	Puriscal	pasture	56-59%	12	37.00		28
Cortes et al 1987	Cot/Tierra Blanca	potato,onion,carrot,pumpkin	66%	4	42600.00		32769
Cortes et al 1987	Cot/Tierra Blanca	potato,onion,carrot,pumpkin	51%	4	4200.00		3231
Cortes et al 1987	Cot/Tierra Blanca	potato,onion,carrot,pumpkin	90%	4	13200.00		10154
Cortes et al 1987	Cot/Tierra Blanca	potato,onion,carrot,pumpkin	40%	4	1800.00		1385

*Values for the Ives (1951) study are reported for the 3 year plot period minus one exceptional storm under the "erosion rate" column. For the Ives study the "exceptional events" column shows separate data for the Dec 6, 1949 storm. Values for the Romero (1991) study have been listed in both columns to emphasize that the erosive events all occurred during 1 month.

**Bubnoff units (B) were calculated from the "erosion rate" column where 1 B = ground loss of 1 mm per 1000 years, equivalent to 1.3 tons km^{-2} yr^{-1} for a bulk density of 1.3 g cc.

Costa Rica, monitoring twelve plots over a period of three years on CATIE's farm. With the exception of a single large storm during the study period, storms resulted in minimal soil loss. Ives attributed the results to the well developed particle aggregation of these soils. High organic matter contents encourage the development of well structured soil aggregates that tend to absorb rainfall and limit runoff. Many of the soils in the Turrialba area, especially those to the east of Turrialba volcano, are ultisols with well developed structure that tends to reduce soil erodibility. The effect of the combination of high organic matter content and well developed structure is made evident when calculating USLE "K" factors from published nomographs for these soils. Calculated "K" factors are very low and even negative in some cases (Van Laake and Hyman, in review).

For plots with poor ground cover in Ives' (1951) Turrialba study area, the single exceptional storm in December 1949 eroded between 20 and 3700 times as much soil in one day than that eroded during the entire three year plot period. No eroded sediments were collected from plots with good ground cover during the storm. Since Ives' study is one of the most complete, it will be discussed later in greater detail.

From the mid-1970s to the present, soil erosion studies carried out through CATIE's Department of Watershed Management corroborated Ives' claim that soil erosion rates are low except for unique events (Rocha 1977, Berru 1980, Mendez 1980, Garzon 1991, Romero 1991, Faustino *et al.* 1994, Lebeuf 1993). Romero (1991) reported values of 28 and 29 tons ha^{-1} during a one month period for plots with beans and bare soil respectively. Except for soil loss during the 1949 storm reported by Ives (1951), these were the highest soil loss values reported among the CATIE studies. The high soil losses in Romero's study are probably due to lack of ground cover, steep slopes (over 55 percent for these plots), and to the exceptional storms that occurred during his study period.

The research in San Juan Sur is particularly instructive on the importance of singular storm events (Faustino *et al.* 1994). For three bare soil plots, two storms were responsible for 89, 53, and 96 percent of the soil eroded during the 12-month plot period. The two storms, on June 17 and July 3, 1993, yielded 84 and 91 mm of rainfall at the nearby CATIE weather station. Faustino *et al.* (1994) cited other work in Costa Rica claiming that about 10 percent of all rainfall events are responsible for 90 percent of the soil erosion. Their work suggested as well the importance of ground cover in reducing soil erosion.

The Puriscal studies (Vahrson and Cervantes 1991b) showed rates comparable to those in the CATIE group. Vahrson and Cervantes (1991b) suggested that rainfall during the plot experiments was erosive by world-wide standards but that due to the permeability of these soils, little erosion occurred. Where runoff occurred, eroded sediments were collected from plots with higher proportions of bare soil. As in Ives' (1951) study, runoff on plots with good cover entrained few sediments.

Cortes *et al.* (1987) found very high soil erosion rates on the slopes of Irazú Volcano. I included this study in **Table 8** to show a significant difference between soils on Quaternary volcanos and those found on older landscapes in the Talamancas such as the Pacuare study area. The slopes of Irazú, Poás and other Quaternary volcanos in Costa Rica are distinct for the physical and cultural processes that influence soil erosion. The farming systems are characterized by intensive vegetable agriculture with high inputs of fertilizers and pesticides, as well as short crop rotation periods that encourage frequent plowing. From a physical standpoint, the soils are young, poorly structured and largely consist of wind blown ash, reflected in high silt contents.

The striking differences between high soil erosion rates on the Irazú slopes and the low erosion rates found in the middle Reventazón valley was confirmed in rainfall simulation experiments by Collinet y Tineo (1995). Soils on the slopes of Irazú (and presumably other Quaternary volcanoes) are young, poorly structured and are erodible due to high silt contents (Tineo 1994). By contrast, the soils on the older Talamanca landscape have had sufficient time to weather to a less erodible loam. High organic matter content of these soils encourages soil aggregation and higher infiltration capacities.

How do the rates reported in these studies compare to typical erosion rates reported in the literature? Saunders and Young (1983) summarized rates of surface wash for world climatic types. The tropical rainforest climate type has the widest range of reported rates of surface wash. The rates reported by Cortes *et al.* (1987) for the slopes of Irazú volcano (greater than 1,000 Bubnoff units B, 1B = 1mm surface lowering per 1,000 years) are in the range of the highest reported worldwide rates. Romero's (1991) studies near La Suiza in the Middle Reventazón watershed reported similarly high rates. Saunders and Young (1983) suggested these high rates can be found in badlands and where soil poorly protected by vegetation is attacked by intense rainfall. The Irazú slopes and the Middle Reventazón watershed are both areas that experience intense rainfall. The studies of Cortes *et al.* (1987), Romero (1991) and Mendez (1980) were carried out for crops with little vegetation cover. Ground cover in coffee fields can vary widely depending on individual farm management practices.

In summary, the plot studies in Costa Rica are in general agreement with the findings of Saunders and Young's (1983). Soil erosion rates in steep and humid areas of Costa Rica are usually low, but some exceptional storms can result in very high rates. On cultivated plots with poor ground cover, high magnitude and infrequent storms can erode large quantities of soil (Ives 1951, Romero 1991, Faustino *et al.* 1994). Severe soil erosion occurs on lands with bare soil. Protective covers such as grass or weeds can prevent erosion during high magnitude storms. However, a broad consensus among researchers on soil erosion processes in Costa Rica is lacking because of the few studies carried out. Considering the sediment yields reported for forested watersheds (ICE 1993), there is an obvious lack of soil erosion plot studies in the tropical rainforest.

Some of the soil erosion plot studies in **Table 8** are noteworthy because high intensity storms of short duration, characteristic of the wet season between June and November, eroded very little soil (Ives 1951, Mendez 1980, Vahrson and Cervantes 1991). Two studies in which large volumes of soil were eroded involved long duration storms (Ives 1951, Romero 1991). Many of the studies (Ives 1951, Mendez 1980, Vahrson 1990, Vahrson and Derckson 1990, Romero 1991) quantified rainfall intensities for durations up to one hour -- the studies show the familiar five, 15, 30 and 60 minute rainfall intensities. Yet, except for Romero's (1990) passing reference to a correlation between total storm rainfall and erosion, none of the studies even mentioned the impact of antecedent rainfall conditions or long duration storms.

The studies of Romero (1991) and Ives (1951) deserve closer attention since their results were the only ones in which considerable erosion occurred. Romero (1991) found stronger relationships between soil erosion and daily rainfall than between soil erosion and rainfall intensities of less than one hour. Since most of the erosion in his study occurred during a long duration storm, saturation may have had an important role in runoff generation.

Ives' (1951) study is particularly notable since only one storm event produced considerable soil erosion during the three-year study period for the Turrialba plots. Short duration storms in almost all cases did not erode sediment. The sediment-yielding storm (December 6, 1949) was the second largest for the 47 year record at CATIE. The automatic recording rain gauge was damaged, preventing data collection at hourly intervals. Local observers estimated that the storm lasted 10 hours, and standard gauges collected approximately 250 mm of rainfall. No erosion occurred on plots with dense vegetation cover. Erosion rates ranged from 78 to 131 tons ha^{-1} for this storm -- extremely high rates -- on the plots with bare soil, cassava, and poorly established kudzu. Rills up to 10 cm in width and 8 cm in depth were formed. Ives (1951) states that "the rate of infiltration had been exceeded by the rate of rainfall at sometime during the storm."

Ives (1951) observed that there was much more runoff and erosion on 16 percent slopes than 45 percent slopes and found it plausible that the greater surface area per unit rainfall on the steeper slopes may result in greater total infiltration. However, if runoff was produced by saturation overland flow, steeper slopes would be expected to produce less surface runoff and greater subsurface throughflow. Infiltrating water on steep slopes reaches the bottom of the slope more rapidly than on gentle slopes because of the greater gravitational forces pulling water downslope. Gentle slopes, on the contrary, become saturated more rapidly due to lower efficiencies of subsurface drainage. Since Ives' plots only measured surface runoff, it is likely that subsurface flow on steep slopes -- being greater than on gentle slopes -- resulted in less water available for surface runoff.

That the two plot studies in which considerable erosion occurred were associated with long duration storms is noteworthy because these storms are the most likely to saturate highly permeable tropical soils. For example, most Costa Rican and tropical soils are highly permeable (Gavende 1968, Buol *et al.* 1989). During many of the plot periods listed in **Table 8**, storms of short duration and high intensity occurred, but they did not erode soil. It appears as though Horton overland flow -- in which rainfall intensity exceeds infiltration capacity -- is not occurring due to the high infiltration capacities of these tropical soils. Because soils of this region have water holding capacities between 100 and 150 mm (Jimenez 1996), it is likely that long duration storms, such as those reported by Romero (1991) and Ives (1951), can produce saturation overland flow. A similar situation was reported by Elsenbeer and Cassel (1990) in Amazonia where perched water tables intersected the ground surface leading to saturation overland flow. Thus, with respect to soil erosion, the long duration storms that saturate the ground are the most important storms for sediment transfer.

Long durations storms, such as the December 1949 storm reported by Ives (1951), are characteristic of important weather phenomenon in the Pacuare basin and surrounding area. They are the so-called "nortes" or "temporales" that originate in North America between December and April. Grandoso (no date) described the pattern in detail in a report on the storm of December 3rd and 4th of 1970. The storms involve large masses of cold air pushing south towards the Caribbean Sea. When these storms occur in Costa Rica, the southern United States may receive unusually large snowfall. As they are frontal systems, they can last from one to four days. **Table 9** shows the annual daily maximum rainfall of the 47 year record at CATIE. Note that maximum daily rainfalls for the 1970 storm and the 1949 storm described by Ives (1951) are identical. The 1970 storm caused one of the largest floods in the Pacuare basin, with a average daily discharge of 817 cms. The largest storm on record occurred in February, 1996. Both Grandoso (n.d.) and Ramirez (1988) state that these storms are characterized by prolonged rainfall of moderate intensity. Of the 15 largest daily rainfall events at CATIE, only one occurred outside the December to April period associated with "nortes," and only 16 of the annual maxima occurred outside of the December to April period for the 47 year period of record. These "nortes" occurring between December and April produce enough rainfall to saturate soils and generate overland flow.

Table 9. Annual 24 hour rainfall maxima and return periods at CATIE

Rank	Rainfall* (mm)	Return Period** (years)	Year	Month	Day
1	314	48.0	1996	2	13
2	288	24.0	1949	12	4
3	288	16.0	1970	4	9
4	248	12.0	1966	2	24
5	241	9.6	1988	1	28
6	220	8.0	1993	12	9
7	176	6.9	1986	3	22
8	166	6.0	1984	12	3
9	154	5.3	1974	12	4
10	152	4.8	1975	12	12
11	150	4.4	1981	11	22
12	148	4.0	1980	12	12
13	144	3.7	1952	10	24
14	140	3.4	1953	1	24
15	131	3.2	1968	12	15
16	131	3.0	1992	5	8
17	127	2.8	1972	8	2
18	127	2.7	1976	1	17
19	124	2.5	1973	12	10
20	120	2.4	1991	8	12
21	120	2.3	1987	12	20
22	115	2.2	1982	7	25
23	110	2.1	1963	12	9
24	109	2.0	1955	10	13
25	109	1.9	1960	12	6
26	109	1.8	1956	1	3
27	107	1.8	1969	11	23
28	107	1.7	1983	3	2
29	106	1.7	1957	11	9
30	104	1.6	1951	2	25
31	102	1.5	1967	7	12
32	102	1.5	1959	4	18
33	96	1.5	1994	6	5
34	96	1.4	1962	11	5
35	96	1.4	1950	2	19
36	91	1.3	1985	9	21
37	86	1.3	1971	7	18
38	85	1.3	1978	12	17
39	85	1.2	1961	12	26
40	84	1.2	1977	6	27
41	82	1.2	1965	3	7
42	78	1.1	1995	2	9
43	78	1.1	1954	12	22
44	67	1.1	1990	6	24
45	65	1.1	1979	4	7
46	65	1.0	1958	5	14
47	61	1.0	1964	6	4

*Rainfall data for CATIE station for period 1949-1996 provided by
Dr. Francisco Jimenez O., Agrometeorologist - CATIE - Turrialba, Costa Rica

**Return periods calculated by the author.

4.3 Field Observations of Surface Wash in the Pacuare.

Since the establishment of long-term soil erosion monitoring was not possible in the scope of this study, I made observations of surface erosion processes in the Pacuare watershed by noting field evidence of rills, gullies, and sediment deposition and by placing sediment traps at selected sites to identify sediment movement on slopes. The short length of the observation period precludes the use of these data to estimate long term surface wash processes. Nevertheless, the field observations do suggest some tendencies with respect to surface wash processes in the watershed. This information, together with the review of past studies, allowed me to develop a conceptual view of surface wash processes, their magnitudes and frequencies, and their importance relative to other sediment transfer processes.

Table 10 shows the results of sediment trap experiments I conducted in parts of the Pacuare basin. I used the work of Lewis (1988) in Rwanda as a model for trap design, but the traps I used were much smaller than his traps and were made of readily available materials. Plastic two-liter beverage bottles were used as shown in **Figure 11.** A slit was made with a knife so that the underside of each bottle exposed a 20 cm long flap style opening. The flap edge was then fixed flush against the ground surface with two 12 cm nails. I installed 55 traps on coffee, sugar cane, forest, and pasture land covers **(Plate 1)**. After attempting to determine the upstream contributing area to each trap, I decided to abandon this effort due to the difficulty of determining the micro-watershed boundary. The ground surface for these land covers is not uniform and is rough due to vegetation, ground litter, and micro-relief. In all cases, the traps were placed at

Table 10. Hillslope sediment traps - Río Pacuare watershed

Trap #	Site	Slope %	Total weight. collected (grams)	Mineral fraction (grams)	Organic matter fraction (grams)	Period days	Loss yr^{-1} (grams) mineral fraction	Loss yr^{-1} (grams) organic fraction	Comment
44	sugar cane	25	0.222	0.161	0.060	92	0.640	0.238	splash
40	sugar cane	24	1.655	1.238	0.417	92	4.910	1.655	runoff and splash
29	sugar cane	15	4.845	3.572	1.273	92	14.172	5.052	runoff and splash
61	sugar cane	10	13.085	9.204	3.881	92	36.515	15.397	runoff and splash
54	sugar cane	25	4.345	3.020	1.325	92	11.982	5.256	splash
52	sugar cane	28	0.979	0.444	0.535	92	1.762	2.122	runoff and splash organic matter
13	sugar cane	24	6.716	4.897	1.819	92	19.429	7.215	runoff
17	sugar cane	20	5.012	3.686	1.326	92	14.625	5.259	runoff and splash
11	sugar cane	24	0.599	0.433	0.166	92	1.719	0.658	splash
12	sugar cane	23	0.849	0.632	0.217	92	2.507	0.859	splash
22	sugar cane	25	0.617	0.500	0.117	92	1.985	0.464	mostly runoff, very little material
26	sugar cane	17	0.664	0.500	0.163	92	1.985	0.648	splash
16	coffee	12	1.909	1.376	0.533	215	2.336	0.904	mostly runoff
42	forest	24	11.135	0.860	10.275	119	2.639	31.515	splash, organic matter, some runoff
25	forest	24	1.724	1.224	0.500	119	3.755	1.533	runoff and splash
65	forest	29	3.385	2.408	0.977	119	7.384	2.997	runoff and splash
51	forest	23	1.349	1.124	0.226	119	3.446	0.692	splash
46	forest	24	1.415	0.906	0.509	119	2.778	1.562	splash
56	forest	20	1.618	1.069	0.549	119	3.279	1.683	some runoff, splash
45	pasture	20	0.160	0.107	0.053	103	0.379	0.187	runoff
63	pasture	16	2.391	1.826	0.565	103	6.470	2.001	runoff

	Average weight mineral fraction (total grams per plot period)	Average weight mineral fraction (total grams per day)	Average weight organic matter (total grams per plot period)	average weight organic matter (total grams per day)
sugar cane	9.353	0.102	3.735	0.041
forest	3.880	0.033	6.664	0.056
pasture	3.424	0.033	1.094	0.011

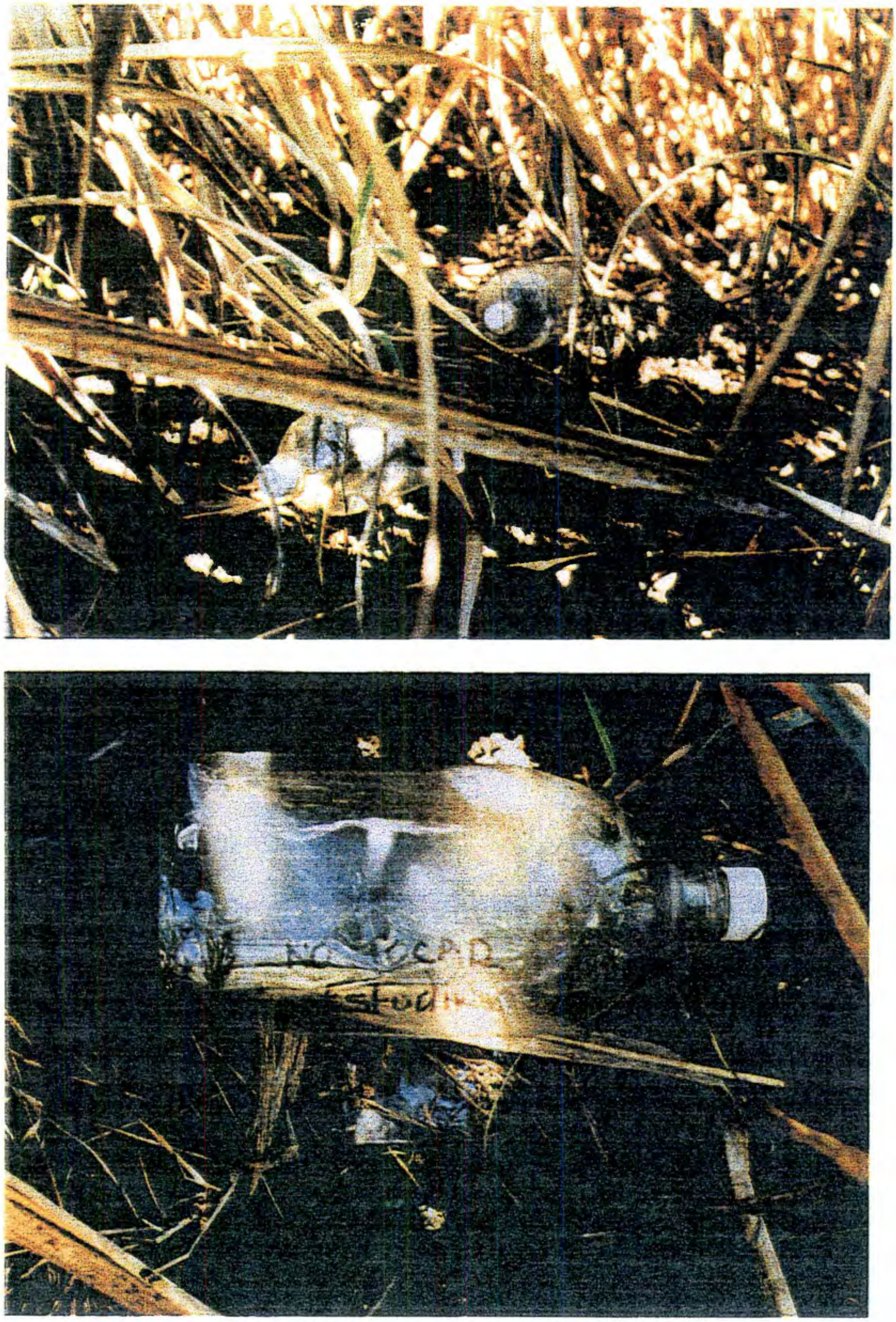

Figure 11. Sediment traps on sugar cane fields.

mid-slope to facilitate comparison. Slope angle on each hillslope was measured with a clinometer. Traps were placed within a 10 km^2 area so that differences in rainfall between sites should not be too great. Because the traps were placed in May, 1995, and then collected at the end of the experiment in December, 1995, no data were collected on surface wash for individual storms. ICE's Pacuar rain gage (station identification number 74005) showed that one large storm of 87 mm occurred on August 24, 1995. On one day in September and two days in October, storms with daily rainfall of 59, 50, and 59 mm occurred.

Unfortunately, I recovered only 21 of the 55 installed traps . About half of the 34 non-recoverable traps could not be found. The remaining non-recoverable traps had been disturbed and were not found in their original position. Many of these sediment traps appeared to be trampled by animals and others may have been disturbed by farm workers. The recovered traps do not well represent the different land uses in the basin. Twelve traps were recovered from sugar cane fields. Six traps were recovered from a forest site. One and two traps were recovered from the coffee and pasture sites, respectively.

I washed the collected soil from the trap into a beaker and allowed it to air dry, noting the appearance of the collected material. The material was then burned in an oven for 12 hours at 450 degrees Celsius to eliminate organic material. **Table 10** reports the quantity of mineral and organic material collected in the traps. I projected the weights of sediment collected during the field experiments to a yearly basis to allow comparison between traps. Also noted in the table is the appearance of sediment moved as runoff and splash. Runoff could be distinguished by the deposition of unaggregated sediments at the bottom of the trap. Splash tends to randomly distribute the soil in the trap and particles are often soil aggregates

Table 10 shows that mineral soil matter trapped on sugar cane fields was considerably greater than that for other land covers. Sugar cane has a highly variable ground cover throughout the year. Before harvest, sugar cane plants provide a thick cover that protects the soil from rainfall attack. The leaves are stripped and left on the ground providing a good mulch cover during the harvest period. The fields are later burned to return nutrients to the soil, leaving the surface ground cover relatively sparse. The sugar cane plants were about 75 percent of their full growth size during the trap plot period. The amount of material collected in the traps on sugar cane fields varied from a low of 0.22 grams to a high of 13.08 grams over a 92 day period. I attribute this variability to differences in upslope microtopography and to how the plant protects the ground surface from falling rain. I observed both runoff and splash in traps on sugar cane fields. On the sugar cane land there was evidence of splash erosion in all sediment traps except one. Even though plant cover may be thick, rain drops falling from leaves can strike the surface and splash soil. In this respect, splash erosion leads to a slow downslope movement of soil particles that may not account for large amounts of material reaching a defined channel. Runoff, on the other hand, is much more likely to reach a channel. But this is not always the case. In the sugar cane fields, small sediment deposits are often seen trapped against organic litter on the surface in much the same way runoff-borne sediment was collected in the installed traps.

The average weight of the mineral fraction in traps on forest land (adjusted to a standard time frame) was about a third of that in the sugar cane fields. The organic fraction was twice that of the sugar cane fields. Splash was found in all traps under forest cover. Forest canopies deliver a large amount of organic litter to the forest floor. The organic material found in the traps tended to be large and identifiable. In a few cases, small twigs and parts of leaves were found in the traps. The amount of material entering the traps could have been limited in some cases by organic material backed up against the trap opening, acting as a barrier to material moving downslope. Likewise, much of the forest floor in this steep environment is characterized by a series of natural barriers to the downslope movement of mineral and organic material. Tree roots are a particularly effective barrier to downslope movement of material. Traps from the forest land cover tended to contain less runoff than those recovered from the sugar cane land cover. Nevertheless, four of the six forest traps had evidence of runoff, indicating that runoff does occur in the forest.

The trap recovered from the coffee field collected 2.3 grams of mineral matter and 0.9 grams of organic material. Coffee fields, like those in sugar cane, can have a highly variable land cover. Seven years are required for a coffee plant to reach full maturity. A less extensive plant canopy protects the surface from raindrop attack during the first few years after sowing the coffee plants. Even mature coffee fields do not provide a closed canopy. The condition of the ground cover also depends on the management efforts of each individual farmer. Many farmers plant trees (leguminous *poro* or banana) to provide shade for the coffee, an extra crop, or nitrogen fixation in the soil. Farmers keep the ground as bare as possible to prevent competition from weeds. In the Pacuare area, much of the weeding work is done manually using machetes. Farmers cannot afford to use large amounts of herbicides, so very few coffee fields were seen with large patches of bare soil exposed. A good mulch cover protects the soil in most cases.

I recovered two traps from pasture areas. Again, the ground surface condition in a pasture is highly dependent on management. Generally, pastures in the Pacuare region, and throughout Costa Rica, have thick grass with very little bare soil exposed. Cattle form terracettes as they traverse steep slopes on most pasture lands. Most of the terracettes do not expose bare soil but exhibit highly compacted soils. However, my observations of pasture fields suggests runoff on these lands contains little sediment. Pasture lands tend to have thick grass with an undulating microtopography. It appears as though thicker grasses found on the pastures in Costa Rica prevents splash and sediment entrainment by runoff, common erosion processes occurring in pastures in drier climates.

Although the results of the trap experiments are inconclusive with respect to quantitative estimates of erosion, the exercise did reveal some tendencies about surface erosion processes on these hillslopes. First, sheet erosion does occur but is held in check by vegetation on the surface. Sheet erosion is not moving huge quantities of soil to the bottom of the slope. Broad-scale sheet erosion across fields, which would be indicated by sediment deposition at the base of slopes, is not occurring. The sheet erosion occurring is variable across the field and depends on microtopography and barriers to downslope movement. Second, splash erosion is occurring and may be important in the gradual downslope movement of surface material. The splash process could be particularly significant given the steepness of the slopes. Third, as may be expected in the wet tropics, a large proportion of the surface material moving downslope is organic matter.

Rills and gullies as they are described in the geomorphological and soil erosion literature are rare in the Pacuare basin, partly because few large fields with extensive bare ground exist. I observed some gullies in poorly managed sugar cane fields, on road cuts, and on trails. The contribution of gully erosion to the total sediment load is difficult to assess. There is no clear pattern of the geographic extent of rill and gully erosion, nor any tendency for the development of rill and gully networks on a systematic basis. In this respect, rill and gully development is similar to that of temperate humid areas such as the eastern United States. Erosional processes producing rills and gullies, such as those found in semi-arid environments where intermittent channels develop, are not evident. The development of rill and gully systems on agricultural lands is probably precluded by high soil infiltration capacities preventing runoff. High intensity rainfall, considered erosive in many environments, rarely exceeds infiltration capacities in the Pacuare area. While rill and gully erosion are occurring on some fields, between fields and on roads and trails, I observed most of these areas without rills and gullies, and suspect this type of erosion is not a major component of the sediment budget.

My field studies and review of soil erosion plot experiments suggested several notable points with respect to the importance of surface wash processes in the sediment transfer system. Although no long term soil erosion plot studies were carried out on forest lands, these areas are clearly susceptible to surface wash. The temporal and spatial variability of surface wash processes is great. Saturation overland flow appears to be more important than Hortonian overland flow in its ability to produce runoff and subsequent erosion. Since soil water holding capacities are usually between 100 and 150 mm of rainfall, storms with a return period of 4.4 years are probably the major events resulting in soil erosion (**Table 9**).

5. THE RIO PACUARE DRAINAGE BASIN: MASS WASTING PROCESSES

5.1. Introduction

Evidence of mass wasting processes is ubiquitous within the Pacuare basin, but the role of mass wasting processes in watershed dynamics has received less consideration in Costa Rica than soil erosion. Field evidence of mass wasting is largely from landslide scars, or from identifiable slide scar patterns of secondary vegetation. Relatively few bare soil scars are visible because vegetation regrowth is rapid. Most of the landslides are what Mora (1985) labels "regolith slides." They do not involve large masses of bedrock but rather are composed of the A and B soil horizons and weathered rock at the soil-bedrock interface. The ubiquity of mass wasting evidence, which is clear from only a brief field visit, raises several important questions with respect to the role of these processes in the overall sediment transfer system. What are the magnitude, frequency and geographic distribution of the processes? How do they function with respect to the entire watershed system? How much sediment do these processes input into the system? In this chapter, I discuss these questions in the context of the two major landslide-triggering mechanisms, rainfall and earthquakes.

5.2. Landslides in the Pacuare Basin Described in Previous Studies.

Three large landslides in the Pacuare basin have been identified that may be best described as earth flows. These deposits cover several square kilometers, have well established vegetation, and have been moving over long periods of time. One landslide, mapped by Madrigal and Rojas (1980), is about

7 km^2 in area and extends into the Reventazón basin near the town (and rainfall station 75004) of Pacuare. In the field, this large feature is not uniform as is shown on the 1:200,000 scale geomorphologic map of Madrigal and Rojas (1980). Some portions of the landslide near the Quebrada Gato exhibit stepped topography similar to a large rotational landslide deposit. In some places, the step scarps expose bare soil, susceptible to rainsplash erosion. But the landslide feature is fully vegetated, with tall trees where land has not been cleared for cultivation, and my field observations suggest it is not presently delivering large masses of sediment to channels.

Another large landslide in the Pacuare basin was studied by Cerdas (1991). This feature is of great interest to ICE because it is located just upstream from the proposed Siquirres hydropower project at Dos Montañas. Cerdas' (1991) analysis of aerial photos showed that the active area of the landslide, about 3 km^2, has been increasing since the early 1950s. However the deposit probably does not yield large quantities of sediment unless a large storm reactivates the unconsolidated sediments. The landslide deposit, like the landslide described by Madrigal and Rojas (1980) near the town of Pacuare, is vegetated with trees as tall as 15 m. Cerdas noted that the 1991 Limón earthquake did not remobilize the sediment deposit. He suggested the deposit might have become activated by the earthquake had there been more water in its soil pores in April, 1991.

Garcia (1995) proposed a third large mass wasting feature between the town of Pacayitas and the main stem of the Río Pacuare, based on his interpretation of radar imagery. Highly unsorted sediment deposits exposed on the banks of the Río Pacayitas suggest a mass wasting origin of the feature and support Garcia's interpretation. The source area of the deposit is the Neogene volcanic feature described by Bergoeing and Malavassi (1982). A former volcanic crater wall could be the source material for much of the deposit. It should be emphasized that this feature, along with the two very large mass wasting features described earlier, have well established vegetation. They are important as sediment sources over the long term because they are unconsolidated deposits, susceptible to river erosion at the toe and to the possible reactivation of the landslide deposit by earthquakes and storms.

5.3 Earthquake-triggered landslides

The Cordillera de Talamanca and the Pacuare region are highly susceptible to mass wasting caused by earthquakes. In order to better understand the relationship between seismic activity and mass wasting, I obtained information on landslides for two large earthquakes and a smaller earthquake in the Pacuare region. I georeferenced remotely sensed imagery to calculate the area affected by landslides triggered from the two large earthquakes. Field observations were made subsequent to the small earthquake. This section discusses the three seismic events and their effects on mass wasting processes in the Pacuare basin.

A magnitude 6.2 earthquake occurred near Pérez Zeledón on the Pacific slope of the Cordillera de Talamanca on July 3, 1983. The earthquake triggered numerous landslides on the Pacific slope, but also affected the uppermost portion of the Río Pacuare basin. I obtained a high altitude color infrared photo

(1:80,000) of the affected area from the Instituto Geográfico Nacional. I was able to scan the photo, taken in April, 1984, nine months after the event, into a digital format and reference it to the digital elevation model of that portion of the basin (**Figure 12**). Unfortunately, all the parameters needed to establish an orthophoto correction were not available. Nonetheless, distances measured on the georeferenced digital photo compare well with distances measured on topographic maps, indicating that the measurements are approximately correct. The light colors on the color infrared images indicate bare soil. The red colors show green vegetation and the black tones indicate water and shadow in steep topography. Land cover is primary rainforest in this part of the basin.

The Pérez Zeledón 1983 earthquake triggered approximately 25 landslides and denuded 286,209 m^2 of forest lands (**Figure 12**). The landslide scars show that many of these mass movements originated at midslope and delivered soil material to channels. The Río Boroi, in the uppermost part of the Pacuare basin, appears to be choked with sediments. It appears white on the image, indicating unvegetated sediments. That the landslides extend down to stream channels suggests an efficient evacuation of sediments. In the lower left portion of **Figure 12**, a 3.4 ha lake formed from the damming of a stream channel by landslide material (indicated by the dark color in the image). Although I did not observe lakes formed by landslide dams during field visits to the watershed, the damming of stream channels by landslide material could be a common process over periods of ten years or greater. The geometry of slopes and channels in the area,

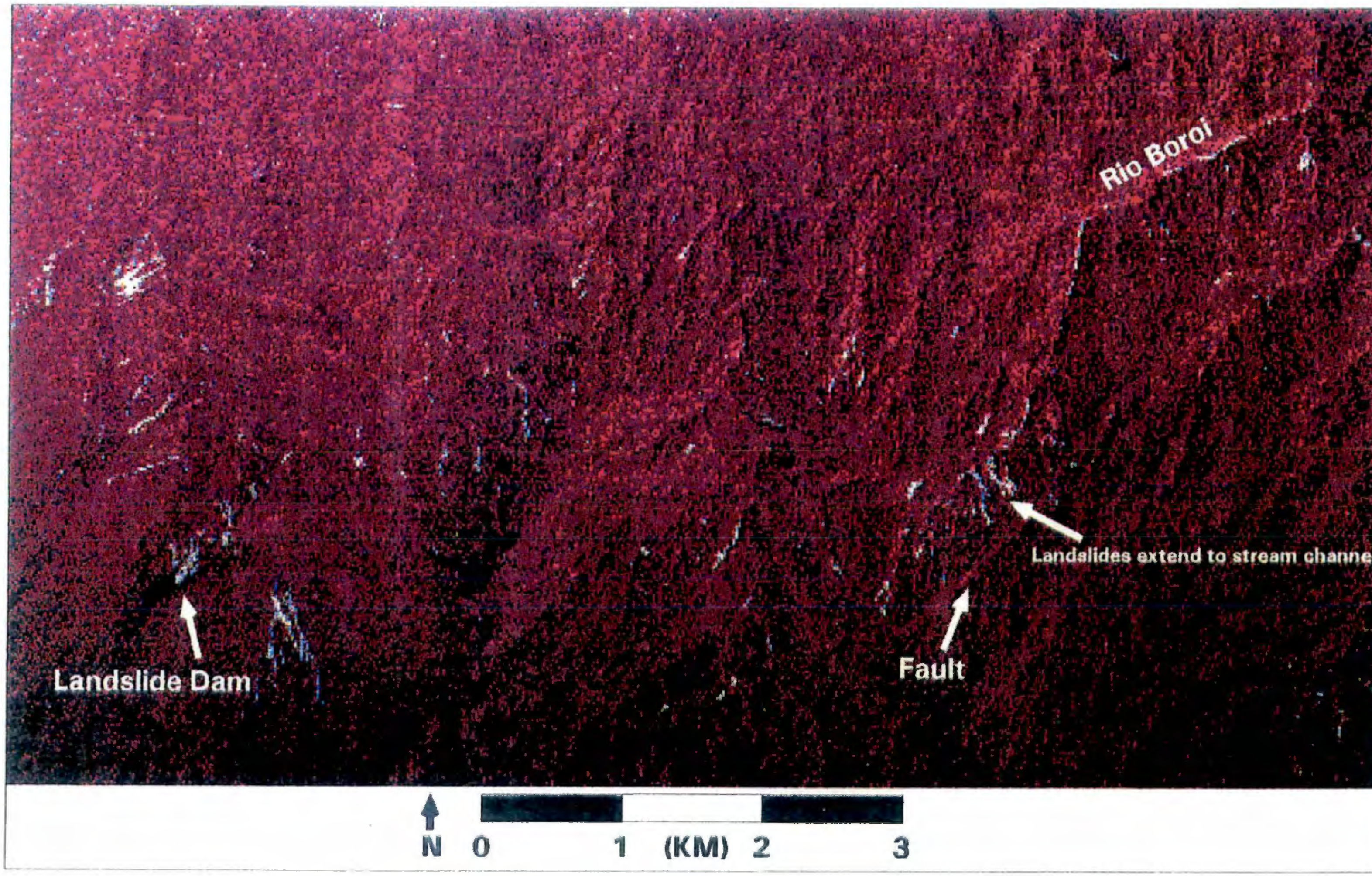

Figure 12. Landslides in the upper Río Pacuare watershed from 1984 infrared aerial photograph. The photograph was provided by IGN. Location of the Río Boroi is shown in Plate 1.

with slopes subject to instability and narrow channels, provide suitable conditions for the development of landslide-dammed lakes. Mora (1985) discusses an example of this phenomenon in the middle part of the nearby Río Telire watershed. Whitewater recreationists have noted, on at least two occasions, sudden waves of sediment laden water which they thought were caused by natural landslide dams that failed (Gallo 1994). These events did not occur in conjunction with storms, further supporting the possibility that a natural landslide dam had failed.

The April, 1991, Limón earthquake generated landslides throughout the Atlantic slope of the Cordillera de Talamanca, affecting the Río Pacuare moderately compared to other areas. Mora and Mora (1994), by surveying damage from a helicopter during the days following the earthquake, estimated a density of one landslide per square kilometer in a 40 to 50 km^2 area of the in the middle part of the Pacuare basin, much less than the Ayil-Boyei sector of the Río Chirripó Atlántico basin where about 240 km^2 were affected. A satellite-derived map of lands denuded from landslides triggered by this earthquake showed that over 100 km^2 of forested land was denuded by mass wasting activity on the Atlantic slope of the Cordillera de Talamanca (Vargas *et al.* 1995). We made the map by tracing affected areas and landmarks on acetate paper, overlaid on a printed copy of the Landsat TM satellite image (Vargas *et al.* 1995). We digitized the traced lines into a GIS and georeferenced the data to 1:50,000 topographic maps. A portion of the map is reproduced in **Figure 13.**

From this map, I calculated that 905,625 m^2 of land had been denuded from the Limón earthquake-triggered landslides in the Pacuare basin. The

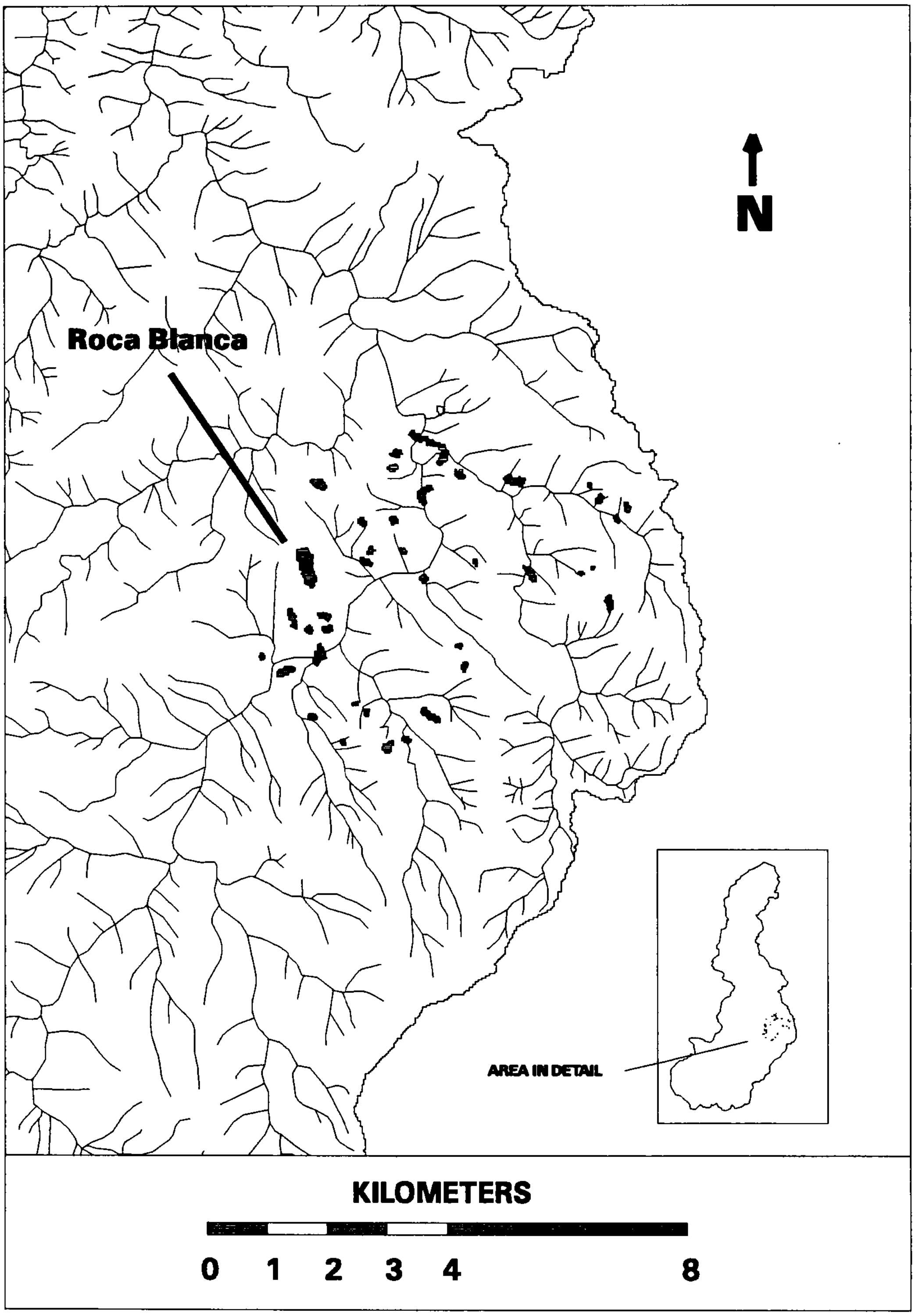

Figure 13. Landslides following the 1991 Limón earthquake in the Río Pacuare. Areas were traced onto acetate paper from hard copy satellite images. The traced lines were then scanned into a GIS and georeferenced to the Lambert projection.

landslide scar areas for the slides shown range in size from 3,125 m^2 to 131,875 m^2, with an average scar area of 22,640 m^2. The landslides shown on the satellite map were not the only ones that occurred in the basin. In July 1991, three months after the earthquake, I counted 54 landslides during a field expedition in a 25 km^2 area along the 17 river kilometers between Tres Equis and Dos Montañas. None of these slides was visible on satellite imagery. They were much smaller than the landslides in the middle part of the basin, normally with scar areas between 1,000 and 1,500 m^2. Apparently, these slides were too small to be detected with the 30 m by 30 m resolution of the Landsat sensor.

Several of the landslides, such as the one shown in the left portion of **Figure 14a,** occurred along the main stem of the Río Pacuare. The Roca Blanca site shown in **Figure 14b**, the largest slide from this earthquake in the Pacuare basin, is not representative of the most of the slides. Here, the failure plane may have coincided with the joint structure of the bedrock. While other landslides moved mostly soil and left behind some weathered material that encouraged rapid regrowth of secondary vegetation, the Roca Blanca landslide scar remains largely unvegetated four years after the earthquake. Since drainage densities are high in the Pacuare watershed, mass wasting processes deliver almost all the landslide deposit to stream channels, an assertion supported by the work of Mora and Mora (1994), Vahrson and Hernandez (1992) and my field observations.

In the Pacuare watershed, the spatial pattern of the landslides triggered by the Limón earthquake may result from proximity to the earthquake epicenter, A

B

Figure 14. Landslides triggered by the Limón earthquake. (a) landslide upstream of Bajo Pacuare. (b) Roca Blanca

about 40 km to the east-southeast of the landslide area shown in **Figure 13.** The landslides, which occurred where the basin bulges out to the east in the approximate direction of the epicenter, are in the part of the basin nearest to the epicenter. The slope map in **Figure 9c** shows that the landslides generated by the Limón earthquake coincide with some of the steepest slopes in the basin. Other studies have suggested that the spatial pattern of landslides from the earthquake depends on the location of faults (Mora and Mora 1994, Vargas *et al.* 1995). The northeast to southwest-trending faults in this part of the basin are noticeable in the drainage network pattern (**Figure 8**). The Limón earthquake-triggered landslides in the Pacuare basin occurred where the main stem of the Pacuare river changes sharply from its northeast trend to a northwest direction.

One interesting aspect of the Limón earthquake event is that it took place during the driest part of the year. I calculated a simple antecedent rainfall index for the period January 1 to April 21 (the day before the Limón earthquake) for some of the nearby rainfall stations based on daily rainfall data and the method described by Dunne and Leopold (1978):

$$I_t = I_0 k^t$$

where I_t and I_0 are values of the antecedent precipitation index on day t and the beginning of the calculation period and k is a constant usually varying between 0.85 and 0.95. I used a value of 0.9 for the calculation of the constant k. The exponent t is the time in days since the last rainfall. The coverage of stations is not extensive enough for a detailed investigation of a possible antecedent rainfall - landslide relationship. However, data from the rain gage closest to the slides (ICE station Rocas Blancas 75007) gave an antecedent rainfall index of 259. For nearby rain gages that had received more rain prior to the earthquake and had indexes of 398 and 361 (ICE station numbers 75003 and 75004 respectively), the map shows no slides, suggesting that soil moisture had little effect on the occurrence of landslides compared to other factors. It is apparent that soil moisture, at much lower levels during the end of the dry season, was not great enough to be an important factor in triggering landslides from the Limón earthquake. What would have happened if this earthquake had occurred during the height of the rainy season when soil moisture levels and pore water pressures would have been at their highest? Since rainfall- generated landslides often occur in this area, the amount of slope denudation would probably have been much greater had the earthquake occurred during the rainy season.

The 1993 Pejibaye earthquake (magnitude 5.3), much smaller than either the Limón or Pérez Zeledón earthquakes, caused some isolated landslides in the Pacuare region (Red Sismológica Nacional 1993). The epicenter was located outside of the Pacuare watershed but along the Attiro fault, which extends across the basin. This part of the Pacuare basin is remote and could not be accessed to survey potential landslide features. A map of modified Mercalli intensities gives a value of between V and VI for the Pacuare basin (Red Sismológico Nacional 1993). This weaker event did not trigger landslides over a wide area. Landslides appeared to be limited to sites particularly susceptible to mass wasting, such as slopes steepened by downcutting stream channels and road cuts. Landslides triggered by this earthquake were much smaller than those triggered by the Limón earthquake (Red Sismológico Nacional 1993). No slides encompassing large sections of a hillslope were observed. In the gorge section of the Río Reventazón near Angostura, at least six landslides were observed with volumes of between 3 and 10 m^3 of material eroded (Red Sismológica Nacional 1993).

Because the Pérez Zeledón, Limón, and Pejibaye earthquakes all resulted in mass wasting phenomena, the magnitude and frequency of landslide-triggering earthquakes can be estimated and compared with other global data. The comparison is complicated due to the influence of other landslide-triggering factors such as antecedent soil moisture, slope characteristics, parent materials, fault structure and distance from earthquake epicenter. Nevertheless, Keefer (1984), in a global study of landslides caused by earthquakes, shows that earthquakes of magnitude 5.0 or greater trigger landslides in steep areas. These figures compare well with Mora and Mora's (1994) review of landslide triggering events in Costa Rica. The triggering of numerous landslides by the 5.0 magnitude Pejibaye earthquake further supports a threshold figure of 5.0 as a lower limit for landslide-triggering earthquakes (Red Sismológica Nacional 1993).

Earthquake frequency at a given magnitude indicates how often landslide-generating seismic events occur. Information on the return period of earthquakes can therefore suggest how often landslide-generated sediments are mobilized. Montero (1986) estimated that for all of Costa Rica, between 1500 and 1820 A.D., earthquakes with a modified Mercalli magnitude VI have a recurrence interval of 13.6 years. The 1993 Pejibaye earthquake registered modified Mercalli magnitudes of VI and VII in the Turrialba and Pacuare area. Near the Nicoya Peninsula, large earthquakes are estimated to recur about every 40 years (Anonymous 1992). Montero (1986) estimated that large earthquakes of magnitude 6.75 or greater have a recurrence interval of 29.5 (+/- 9.9) years for the Central Valley. The largest earthquakes in Costa Rica probably have a recurrence interval of 50 years on the Pacific slope and about 150 years on the Atlantic slope (Peraldo 1995).

I obtained additional data from the NOAA Earthquake Data Base for a 1 degree square area in the Cordillera de Talamanca (83° to 84° WEST and 9° to 10° NORTH, approximately 110 by 110 km). This 1 degree square area, centered over the Pacuare drainage basin, includes all earthquake epicenters within 65 km of the watershed. **Table 11** shows the annual maximum event ranked from greatest magnitude to least magnitude. The values are the highest reported from a world-wide network of seismological stations and therefore overestimate the magnitudes. For example, local seismological networks reported magnitudes of 7.5 for the 1991 earthquake and 5.3 for the 1993 earthquake, compared to NOAA's figures of 8.1 and 6.1, respectively. Thus, the magnitudes reported by NOAA overestimate the locally derived magnitudes by about 0.6. The data are misleading for the event of greatest magnitude due to the short history of seismological monitoring. But for middle part of the series, the magnitudes are more likely to be correct.

Adjusting upward by 0.6 to account for the overestimation in the NOAA data, **Table 11** shows that earthquakes with magnitudes between 5.0 and 6.0 have recurrence intervals of between 6.6 and about 15 years in the 1 degree square area centered on the Río Pacuare drainage basin. On average, landslide-triggering earthquakes occur about every 7 years. The frequency of earthquakes that trigger numerous landslides, such as the Pérez Zeledón earthquake, is

Table 11. Earthquake recurrence intervals for 1 degree square area centered over the Río Pacuare watershed in the in the Cordillera de Talmanca

Year	Magnitude*	Rank	Recurrence Interval
1991	8.1	1	33.0
1983	6.7	2	16.5
1993	6.1	3	11.0
1974	5.8	4	8.3
1994	5.6	5	6.6
1976	5.5	6	5.5
1973	5.3	7	4.7
1985	5.1	8	4.1
1984	5	9	3.7
1987	5	10	3.3
1990	4.9	11	3.0
1992	4.9	12	2.8
1988	4.8	13	2.5
1966	4.7	14	2.4
1989	4.6	15	2.2
1980	4.5	16	2.1
1964	4.5	17	1.9
1969	4.4	18	1.8
1995	4.3	19	1.7
1963	4.2	20	1.7
1977	4.2	21	1.6
1968	4.1	22	1.5
1972	3.9	23	1.4
1986	3.8	24	1.4
1965	3.8	25	1.3
1970	3.7	26	1.3
1978	2.9	27	1.2
1975	0	28	1.2
1967	0	29	1.1
1981	0	30	1.1
1982	0	31	1.1
1971	0	32	1.0
1979	0	33	1.0

Source: NOAA Earthquake Information Database

* magnitudes of zero indicate no earthquakes occurred in the study area during that year.

difficult to estimate, but may be, on average, 20 to 30 years. The Limón earthquake was the largest of record for the data shown in **Table 11.** Peraldo (1995) suggested this earthquake may have a recurrence interval of 100 years.

When relating earthquakes to mass wasting, it is very difficult to model the spatial variability in landslide occurrence. For example, the Limón earthquake affected about 1 km^2 in the Pacuare basin, compared to about 50 km^2 in the adjacent Río Chirripó Atlántico basin. Thus, we could say that, on average, every 100 years we could expect 1 to 50 km^2 of denudation from large earthquakes in the Cordillera de Talamanca. However, the area affected by large earthquakes is probably some intermediate value between these two extremes.

5.4. Rainfall-Triggered Landslides

The other landslide triggering mechanism common in Costa Rica is rainfall. Landslides triggered by rainfall exhibit great spatial and temporal variability. They tend to be small in size compared to earthquake-generated landslides. It is difficult to determine the storm magnitude necessary to trigger a landslide. Many factors such as antecedent soil moisture and local environmental conditions operate together with the storm to trigger landslides (Baird and Harden 1995). The following are some accounts of Costa Rican landslides triggered by rainfall. They show the rainfall conditions associated with landslides in areas near the Pacuare basin.

Mora *et al.* (1989) described an extreme rainfall event that triggered numerous landslides near Pejibaye in July 1987 -- an area 10 km away from the Pacuare basin. In a 25 km^2 area, 275 mm of rain fell in a within a period of five hours. Landslides completely altered over 1,000 ha, and about 1,300 ha were partially damaged. The landslides delivered trees, roots, and soil to stream channels. Mora *et al.* (1989) attributed the extensive landslide erosion to saturation of soils on steep slopes. They did not present information on the return period of the storm and long-term precipitation data for nearby stations were unavailable. However, for the CATIE station 9 km to the northeast, this storm corresponded to the 15 year return period storm. The storm event is unusual because it lasted about five hours and was localized in the Pejibaye area.

Some historical landslides were documented as part of a country-wide survey of mass wasting phenomenon (Peraldo and Mora, in preparation). The survey is still in an early stage but records for five landslide events in the Turrialba area are available. **Table 12** lists these five events along with the 1996 storm in Turrialba. Rainfall conditions at three rain gages in the area are listed. The survey data do not include landslide volumes or areas. Since the data are taken from newspaper articles and from reports of road and railroad closings, it is not known if these events are broadly representative of mass wasting processes in the area. Landslides that did not affect human populations are not listed. Thus, the data suggest neither absolute magnitude nor frequency of the mass wasting in the Turrialba area. Nevertheless, the data indicate the prevailing rainfall conditions that triggered landslides. Considerable rainfall leading up to the date of the landslide occurred in all five cases shown in **Table 12.** The minimum rainfall in the days prior to the landslides was 49 mm and

Table 12. Rainfall conditions associated with historical landslides in the vicinity of Turrialba

DATE OF LANDSLIDES*	LOCATION	RAINFALL CONDITIONS**		
		Siquirres	Pacuare	CATIE
July 12, 1971	Siquirres/Turrialba	85 mm on 9th and 10th of July	no considerable rainfall	49 mm in 2 days prior
November 26, 1975	Las Lomas	394 mm in 4 days prior	96 mm in 3 days prior	152 mm in 6 days prior
December 14, 1980	Río Reventazón	943 mm in 3 days prior	507 mm in 3 days prior	255 mm in 3 days prior
June 21, 1985	Codo del Diablo, Las Lomas El Rubi, San Antonio, Altos de Guayacán	90 mm on June 20	66 mm on 2 days prior	91 mm on 3 days prior
December 11, 1993	Campabadal, Turrialba	no considerable rainfall	144 mm on 9,10, 11 December	397 mm on 9th and 10th
February 13, 1996	Turrialba	data unavailable	data unavailable	314 mm on July 13th

*landslide information is from Peraldo y Mora (in preparation) and Peraldo (1996)
** rainfall conditions are from data provided by ICE for the Pacuare and Siquirres stations.
CATIE station data were provided by Dr. Francisco Jimenez, CATIE.

the maximum was 943 mm.

A large storm occurred in the Pacuare basin on December 9, 10 and 11, 1993, resulting in numerous landslides. The rainfall gage closest to these landslides (Pacuar 75005) recorded a daily value of 294 mm of rainfall, equivalent to the five-year recurrence interval storm for that station. At CATIE, 220 mm of rainfall were measured, equivalent to the eight-year rainfall for the 47-year record. Local news reports described the storm as typical of the "nortes" that occur in December. **Figure 15** shows the right bank of the Río Jicotea watershed, a subwatershed of the Río Pacuare basin, where several landslides from the December, 1993, storm can be seen. By sketching landslide locations on topographic maps and by rough field calculations, I estimated that about 15,000 m^2 of hillslope were affected in the Río Jicotea watershed.

Landslides occurred on both cultivated and forested slopes. I have not seen any relationship between land cover and landslides in the Pacuare region. Landslides are found in all land covers. Because forests are more likely to be coincident with steep slopes, relative to cleared lands, the two land cover types cannot be easily compared. In general, slope steepness together with rainfall appear to be the critical factors in the triggering of these landslides.

Most of the Río Jicotea landslides occurred on side slopes with very little curvature. One exception is the landslide that occurred near La Mina. **Figure 16** shows the deposited material from the La Mina landslide. The photo was taken several months after the storm, and vegetation is already established. Note how the deposit is unsorted, with boulders lying near the surface. The landslide occurred where both the plan and profile slope curvature are convex. Deposits

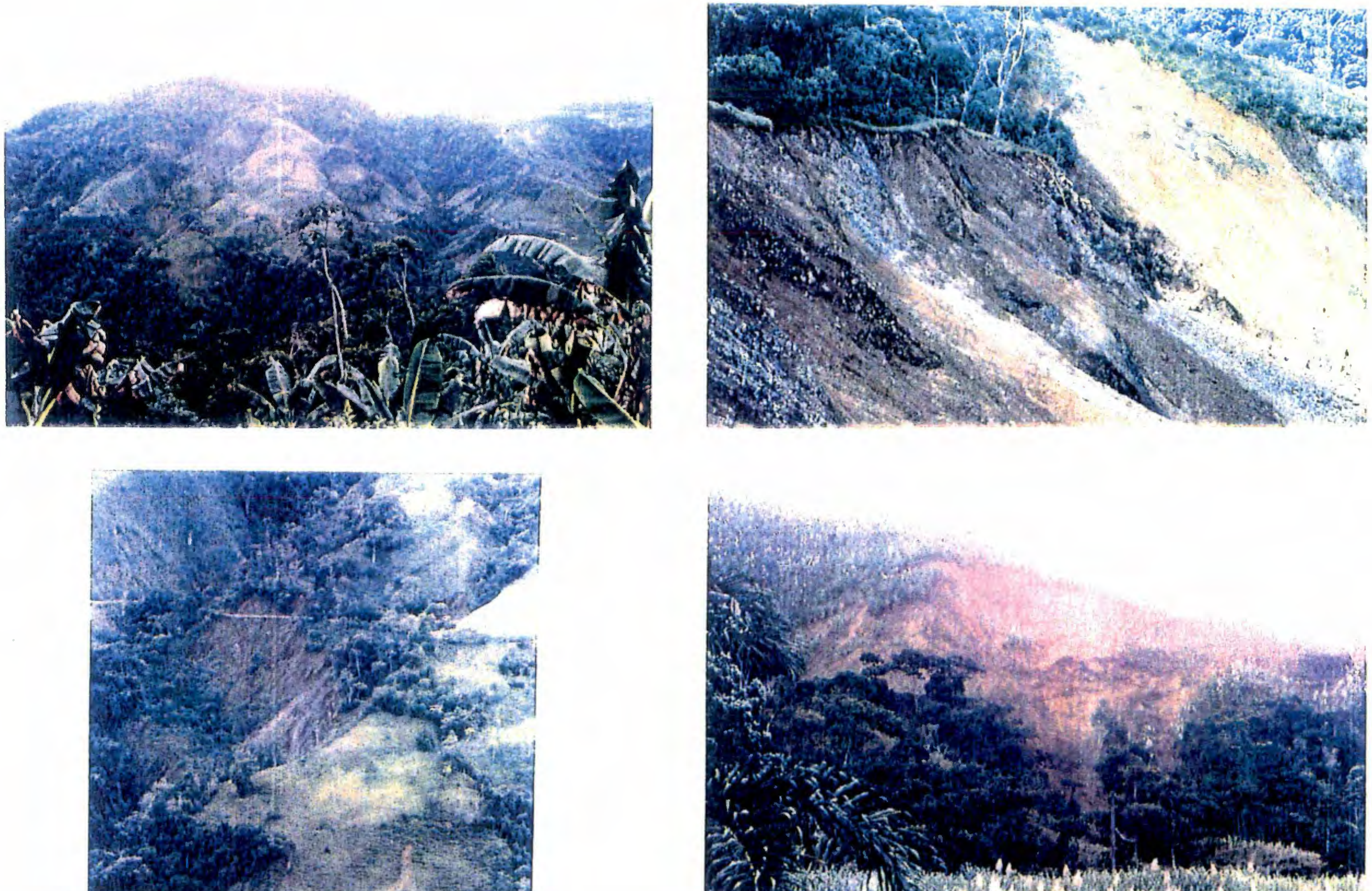

Figure 15. December 1993 landslides in the Río Jicotea watershed, tributary to Río Pacuare. The landslides affected about 15,000 m^2.

Figure 16. Landslide deposit at La Mina.

such as the one near La Mina can be found throughout this region. In many cases, the landslides occur in low order intermittent stream channels. They fill the channel, which subsequently begins to cut its way through the colluvial deposit, a process that is probably rapid. The banks of these intermittent channels are composed of unsorted colluvial deposits. The landslide material is viscous enough to leave a highly unsorted deposit. Evidence of the deposit are the boulders that are often seen lying at the soil surface with small particles beneath them.

5.5 Conclusions on the Role of Mass Wasting in Sediment Transfer in the Río Pacuare Watershed.

With respect to mass wasting processes in the Pacuare watershed and surrounding areas, several points merit attention. First, evidence from field expeditions in the lower Pacuare gorge and from remotely sensed data suggest landslides deposit sediments at the bottom of slopes and in defined, though perhaps intermittent, channels. Second, landslides occur in many different parts of the Pacuare basin and in different topographic situations. The earthquake-generated landslides of 1983 and 1991 occurred on some of the steepest slopes in the basin, occurred on straight slope segments, and may be related to fault location. The Río Jicotea landslides, generated by a storm, also occurred on steep slopes, and a prominent landslide originated where plan and profile slopes converge. Third, events that trigger landslides occur often enough to make landslides important components of the sediment transfer system. Storms that trigger landslides, such as the December 1993 storm in the Pacuare watershed, occur about every five years **(Table 9)**. Earthquakes that trigger landsides occur, on average, every six to ten years **(Table 11)**. Thus, earthquakes and storms trigger landslides three to four times each decade.

6. THE RIO PACUARE DRAINAGE BASIN: CHANNEL PROCESSES

6.1. Introduction

Once sediments have become mobilized in a drainage basin, they can either be carried out of the system or deposited downslope or downstream. The ease or difficulty with which a watershed system evacuates sediments is an important characteristic because it determines the nature of depositional landforms, the level of pollution, and resource use potential. The previous chapters focused on surface wash erosion and mass wasting in the sediment dynamics of the Río Pacuare basin, the two principal components of sediment production. This chapter deals with the channel system in the Río Pacuare watershed, focusing on evacuation of sediments. Is sediment delivery transport- or supply-limited? How do rainfall and earthquake events affect sediment loads? Where do sediments in channels originate? I measured sediment concentrations in tributaries to the main stem of the Pacuare river. I discuss tributary stream sediment concentrations and those measured by ICE at the two main stem gaging stations in the following sections.

Channels of the Pacuare river and its tributaries flow on bedrock or on relatively thin layers of boulders, cobbles, and sand (**Figure 17**). Bedrock banks are ubiquitous. In the gorge sections, waterfalls are common, indicating rapid tectonic uplift and river downcutting. The extent of flood plains is limited to a very few areas with flat channel slopes and to small alluvial fans where tributary streams join the main stem. Throughout most of the main stem channel, the sediments follow a pool and riffle sequence. Several exceptions to the pattern can be observed in lower parts of the watershed. Between Bajo Tigre

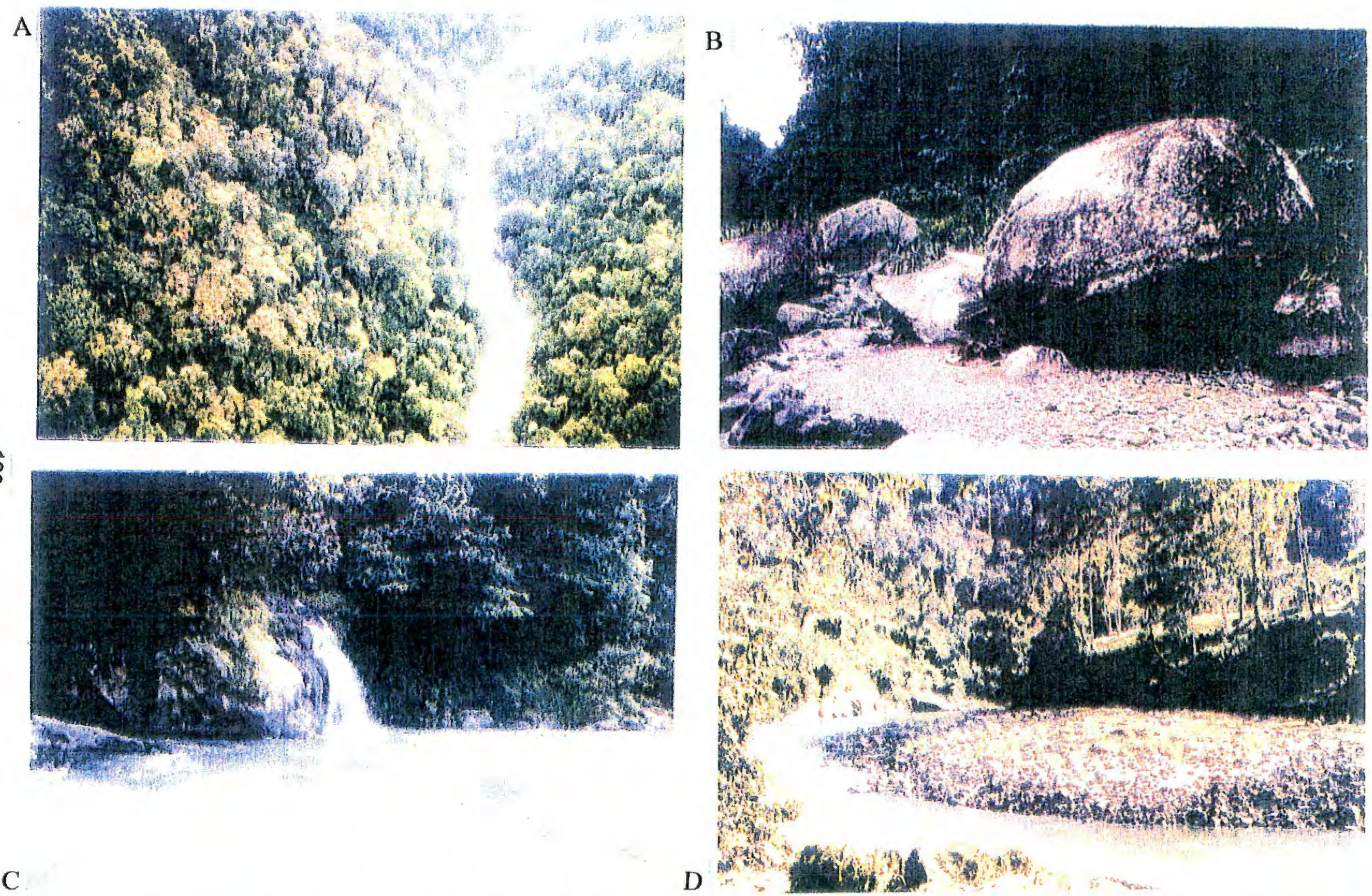

Figure 17. Channel conditions in the Río Pacuare watershed. (a) narrow channels without floodplains. Photograph courtesy of Rafael Gallo.(b) large rounded boulders on channel bottom (c) waterfalls entering the main stem of the Río Pacuare suggest rapid tectonic uplift and river downcutting. (d) boulder and cobble bar adjacent to bedrock channel and banks.

and 1 km downstream of Bajo Huacas, river slope increases and the channel is composed of many more large boulders. This section has the largest rapids. The large meander bend between Quebrada Quebradon and Dos Montañas is characterized by more gentle channel slopes. A large alluvial fan composed of small boulders, cobbles, and sand follows the left bank of this section. At Dos Montañas, a large concentration of boulders funnels into the narrow gap. The upper watershed has similar areas of typical pool and riffle sequences broken up by gorge areas and relatively gently sloping sections.

Sediment bedload has not been measured on the Pacuare river. The proportion of sediment that is transported as bedload relative to total sediment load could be much higher than the 10 to 20 percent estimated for many rivers. One study has shown that bed loads in steep humid-tropical watersheds of Puerto Rico make up between 34 and 92 percent of the total sediment load (Simon and Guzman-Ríos 1990). The narrowness of channels, lack of flood plains, large sediments in the channel, bedrock banks, and the channel slope all indicate that the river efficiently transports available sediments. Storage times for sediment are short.

6.2. Suspended Sediment Concentrations in Tributary Streams

One way to determine the sources of sediments in the watershed is to measure sediment concentrations in different tributary streams and compare them. Towards this objective, I collected water samples on tributary streams of the main stem of the Pacuare river. **Table 13** shows the distribution of land covers within the selected subwatersheds. **Figure 18** shows the basins I

Table 13. Land cover in selected subwatersheds of the Rio Pacaure basin

	Quebradon		Ganga		Alcantrilla		Platanillo		Jicotea		San Rafael		Molejones	
	area km^2	%	area km^2	%	area km^2	%	area km^2	%	area km^2	%	area km^2	%	area km^2	%
forest	3.69	44.30	0.49	9.53	8.41	75.16	3.15	52.68	10.85	55.08	2.96	45.33	4.37	87.93
secondary forest	3.77	45.26	1.29	25.10	1.14	10.19	1.14	19.06	3.95	20.05	1.32	20.21	0.39	7.85
coffee	0.04	0.48	1.21	23.54	0.15	1.34	0.80	13.38	1.59	8.07	0.79	12.10	0.02	0.40
sugar cane	0.00	0.00	0.07	1.36	0.13	1.16	0.18	3.01	0.73	3.70	0.05	0.77	0.05	1.01
pasture	0.80	9.60	2.07	40.27	0.08	0.71	0.67	11.20	2.22	11.27	1.40	21.44	0.08	1.61
shadow	0.03	0.36	0.00	0.00	0.87	7.77	0.00	0.00	0.02	0.10	0.00	0.00	0.00	0.00
urban	0.00	0.00	0.01	0.19	0.41	3.66	0.04	0.67	0.34	1.73	0.01	0.15	0.06	1.21
total	8.33	100.00	5.14	100.00	11.19	100.00	5.98	100.00	19.70	100	6.53	100	4.97	100

Note: Land cover was determined by the author from satellite-derived data described in Chapter 3. Areas were calculated using GIS software.

Figure 18. Subwatersheds of the Río Pacuare selected for suspended sediment sampling.

selected for sampling. The selection of these basins was based on ease of access and for purposes of comparison. There are always considerable difficulties establishing sediment sampling programs for streams, especially in small mountainous watersheds. These are compounded in the Pacuare basin by difficulty of access. Nevertheless, measurements taken in these tributary streams suggest some general principles. All the subwatersheds have a large proportion of their area in forest as is true for the Pacuare basin as a whole. The Alcantrilla, Quebradon, and Molejones basins have the highest percentage of forest. The Ganga and San Rafael basins have large areas in cattle pasture. The Platanillo and Jicotea basins comprise large areas of coffee and sugar cane.

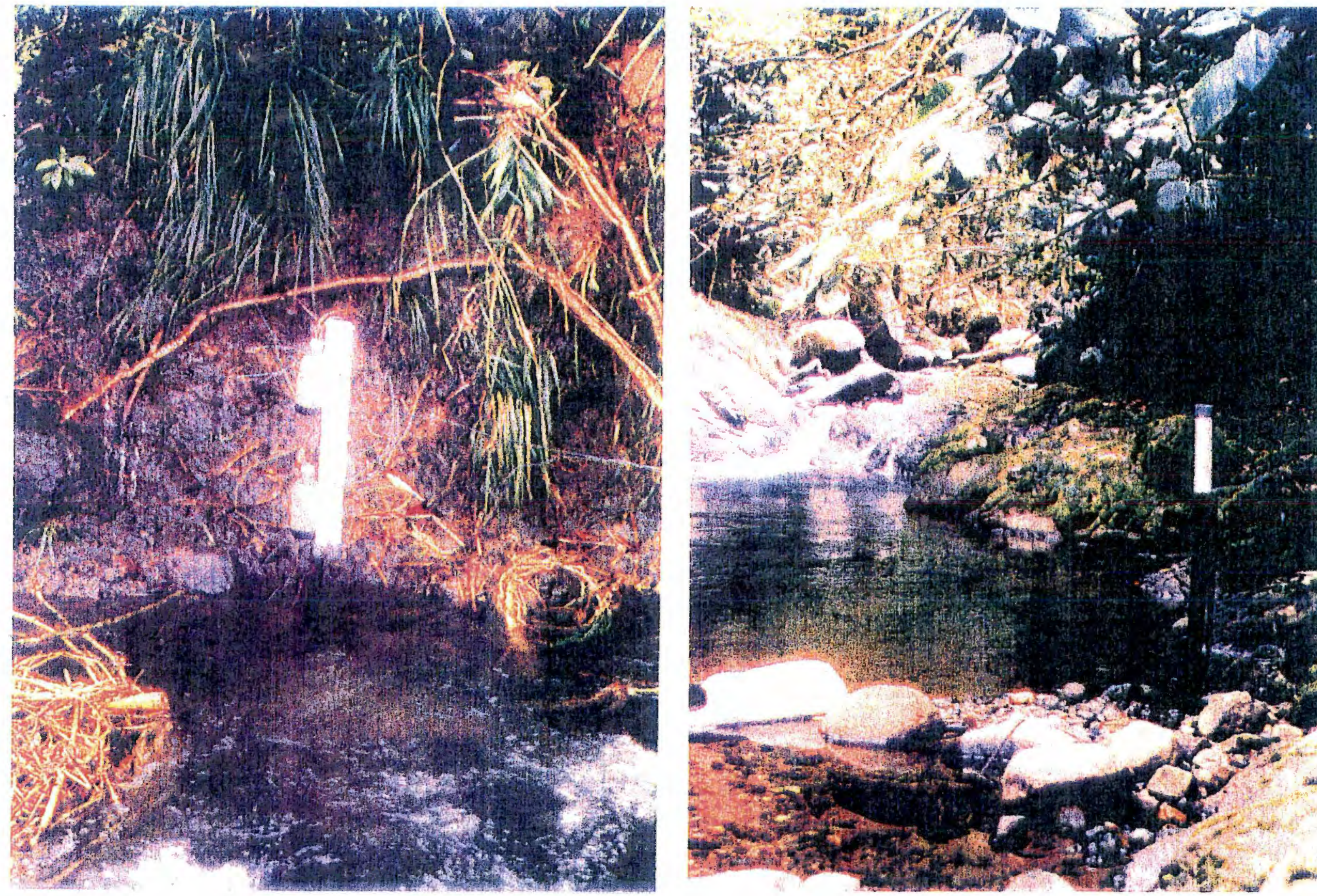

Figure 19. Crest stage gages with rising stage samplers

In each tributary stream, I surveyed a cross section and set up a staff gage. I made the gages from thick metal rods and pounded them into the channel bottom with a sledge hammer, as shown in **Figure 19.** Plastic PVC tubes were attached to the rods to measure the crest stage (Miller and Leopold 1963). Gage heights were marked on the PVC tube.

It was not feasible for me to measure discharge during storms due to the danger of wading these streams during high flows. I made one or two low-flow discharge measurements at each tributary cross section with a current meter. I estimated discharges for the gage heights, based on hydraulic geometry of the cross section. The cross section was surveyed using a Teledyne leveler to place a wire across the channel. Depths were measured with a staff ruler. The leveler was used to measure channel slope across a 30 m channel section. The hydraulic geometry measurements were used with Manning's equation to estimate velocities. I fitted the water rating curves by eye. They are based on the estimated discharges and are presented in **Appendix 1**. I used these curves to match sediment concentrations with their respective discharges.

I attached rising stage samplers to the gages to collect water samples at different gage heights. The sampler, modified from a design described by Lewin (1981), is made of plastic soft drink bottles with copper tubing. I drilled holes into the bottle caps and inserted the copper tubing. As streams rise, the water enters the lower tube, pushing air out through the upper tube. Once water has risen to the level of the air outlet, the sampler will no longer take in water. Samplers were wired to the crest stage gages at varying heights.

Growth of organisms in the water sample is a potential problem for any sediment sampling program (Guy 1970). Most programs do not include methods to remove organic material. I did not use any method to eliminate organic matter from my samples, other than prompt lab analysis and refrigeration of the sample so organisms would have less opportunity to grow. In all cases, bottles were retrieved within two days of a storm event. If algal growth appeared in the water, the sample was discarded. Sample bottles were placed in a refrigerator and analyzed within seven days of their collection.

I measured concentrations using the filtration method (Guy 1969). The sample bottles and water sample were weighed to 0.01 grams. The filter paper and sediment sample were weighed on an analytical balance to 0.0001 grams. I used a electric-powered vacuum pump to filter the water sample through 0.45 micron glass fiber filter paper. The filter paper with its sediment residue was left in an oven overnight to eliminate moisture. After dessication, the paper was weighed again, with the result subtracted from the original filter paper weight to obtain the dry weight of the sediment. Sediment concentration values are reported as the proportion of the sediment weight to the sample weight converted to milligrams per liter (Porterfield 1972). **Appendix 2** shows the results of the laboratory analysis and **Figure 20** presents the sediment concentration plotted against discharge in a graphic format. The discharges are expressed per unit area to allow comparison between sub-watersheds.

No strong patterns are evident from this graph but some conclusions can be made. The data presented here suffer from the few number of samples, and are inadequate for a rigorous statistical analysis. The results confirm Walling

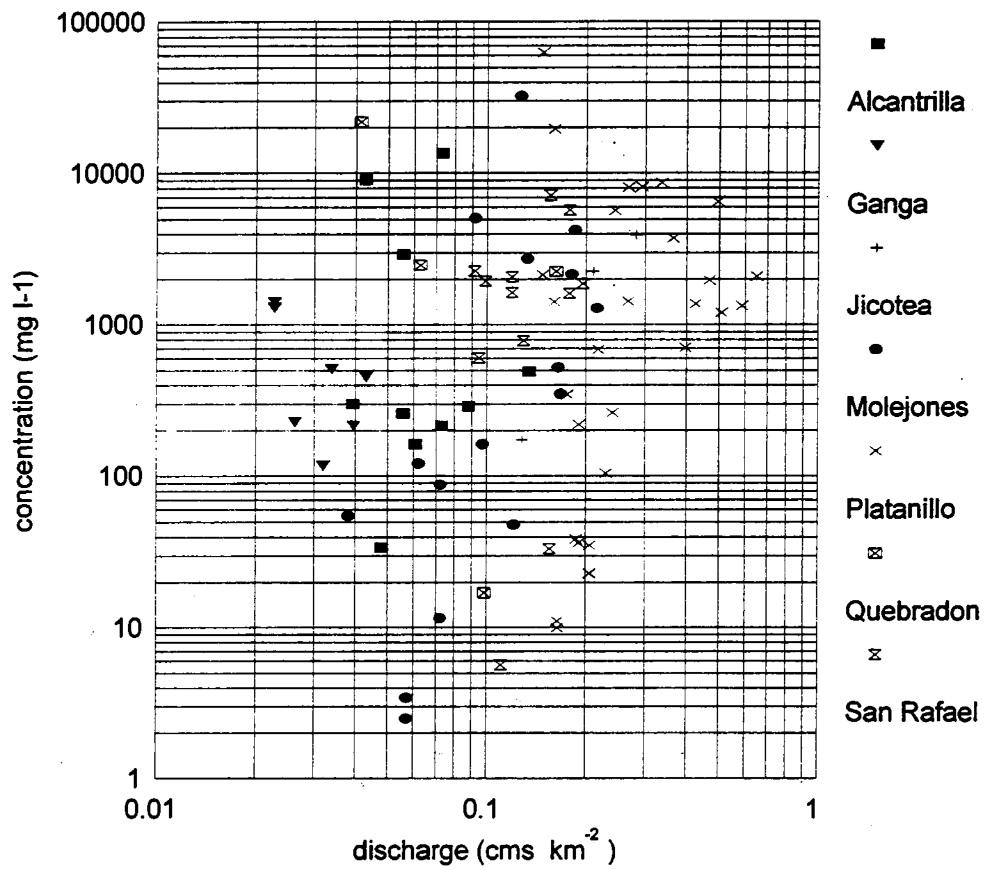

Figure 20. Concentration - discharge relationship for selected Pacuare subwatersheds

and Webb's (1982) study of storm concentrations and suggest that average figures for storm period sediment concentrations could be used to calculate storm sediment loads. For small streams, storm concentrations tend to cluster and do not show the log linear relationship often plotted for sediment concentrations in large rivers. The data reinforce the notion that other factors in addition to runoff are important for delivering sediment to stream channels. All the basins except the Ganga basin show a wide range of sediment concentrations at similar discharges. In most cases, the concentrations range from about 10 mg l^{-1} up to 10,000 mg l^{-1}. Streams rise, but their turbidity at high flow levels depends on numerous factors in addition to the quantity of water leaving the basin. These factors probably include mass wasting activity, antecedent soil moisture, vegetative cover, and human impacts.

Table 14 shows the average storm sediment concentrations for each tributary stream. There are too few measurements to allow conclusions about sediment behavior with certainty. Nevertheless, it is noteworthy that the highest average sediment concentration (4,772 ppm) was found in the Platanillo watershed, which has large areas of sugar cane cultivation. The second highest average was found in the Gato watershed, which has a large area in coffee cultivation. Discharges for the Gato watershed could not be calculated because the crest stage gage was damaged by storm flow. A period of slope instability associated with high rainfall occurred in this basin during 1970. A part of the Gato watershed was mapped as a large earthflow by Madrigal and Rojas (1980). The average sediment concentration of the Alcantrilla, Molejones, and Quebradon drainage basins, those primarily in forest cover, was about 60

Table 14. Mean storm sediment concentrations for selected subwatersheds of the Río Pacuare

Tributary	Predominant land cover	Number of observations	Mean storm sediment concentration (ppm)*
Alcantrilla	forest	10	2720
Ganga	pasture	7	602
Gato**	coffee, pasture	5	5328
Molejones	forest	16	3072
Platanillo	sugar cane / forest	28	4772
Quebradon	forest / pasture	5	2911
San Rafael	pasture / forest	11	2143
Jicotea	sugar cane / coffee / fore	2	3103

*Distribution of the data is shown graphically in Figure 20.
**Note that no information is given for the Gato basin in Figure 20 and Table 13. Discharge information was not collected because the staff gage was damaged.

percent of the mean concentrations of the Platanillo and Gato tributaries, drainage basins with the largest areas of sugar cane and coffee. This result is noteworthy if compared to temperate basins where sediment concentrations for forested basins are typically much less than half of measured concentrations in cultivated basins (Douglas 1990).

6.3. Main Stem Sediment Yield

The previous section focused on suspended sediment in tributary streams during a short period of field observations. ICE has monitored suspended sediment concentrations on the main stem of the Pacuare for a period of 25 years. ICE began its sediment monitoring program on the upper watershed at Bajo Pacuare (drainage area 367 km^2) in 1968 and at Dos Montañas (drainage area 651 km^2) in 1970. **Table 15** shows the reported sediment loads for these two stations as calculated by ICE (1993) for the hydrologic years (May through April) 1971 to 1991. At Bajo Pacuare, reported annual sediment loads range from 38,075 tons to a maximum of 357,924 tons. The Dos Montañas sediment loads range from 107,114 to 706,848 tons. Not shown are loads for the hydrologic years 1969 and 1970, since the Dos Montañas station had yet to give a full year's data. ICE (1993) reports sediment loads for the Bajo Pacuare station of 759,623 and 762,688 tons for those two years respectively. Unfortunately, the sampling record is rather short. As with many sampling programs, low discharges are over-represented and relatively few samples exist for high discharges. This makes it difficult to compare the concentration data with sediment producing events or periods of the year with greater probability of producing sediment.

The difference in sediment loads between the entire watershed (Dos Montañas) and the upper watershed (Bajo Pacuare) gives a measure of sediment derived from the lower portion of the basin. **Table 15** shows that the 283 km^2 lower watershed on average contributes half of the sediment of the 651 km^2 basin. The lower watershed contributes over 1.6 times more sediment per unit area compared to the upper watershed, a difference in sediment load that can be attributed to the difference in land cover. The upper watershed is almost entirely forested. Forty percent of the lower watershed has been deforested.

Table 15. Annual Suspended Sediment Loads in the Río Pacuare Watershed

Hydrologic Year	Suspended Sediment Load*						% contribution lower watershed
	Bajo Pacuare		Dos Montañas		Difference**		
	tons	tons km^{-2}	tons	tons km^{-2}	tons	tons km^{-2}	
1971	103,680	283	172,801	265	69,121	244	40
1972	175,575	478	258,040	396	82,465	291	32
1973	199,483	544	705,331	1083	505,848	1787	72
1974	138,542	377	706,848	1086	568,306	2008	80
1975	357,924	975	566,617	870	208,693	737	37
1976	118,184	322	540,359	830	422,175	1492	78
1977	46,700	127	148,395	228	101,695	359	69
1978	58,925	161	108,740	167	49,815	176	46
1979	76,454	208	120,317	185	43,863	155	36
1980	143,759	392	446,010	685	302,251	1068	68
1981	146,596	399	287,452	442	140,856	498	49
1982	74,997	204	165,546	254	90,549	320	55
1983	251,669	686	199,482	306	-52,187	-184	-26
1984	101,736	277	188,677	290	86,941	307	46
1985	38,075	104	154,929	238	116,854	413	75
1986	82,295	224	144,461	222	62,166	220	43
1987	137,467	375	271,632	417	134,165	474	49
1988	124,893	340	190,336	292	65,443	231	34
1989	78,292	213	107,114	165	28,822	102	27
1990	174,905	477	340,217	523	165,312	584	49
1991	48,810	133	311,772	479	262,962	929	84
Average	127570	365	292146	471	164577	611	49

*Source: ICE (1993)
**This column, calculated by the author, shows the difference between the load calculated for the upper watershed and that calculated for the entire watershed. Thus, the column indicates sediment load for the lower watershed. Note that for 1983, ICE calculates a sediment load greater in the upper watershed than that for the entire watershed. This condition could only occur if there was large net sediment deposition in the lower watershed. However, the result is more likely due to inherent errors of the sediment rating curve technique (See Walling 1988 for a discussion of problems of the technique).

Other factors such as distance to outlet, steep and unstable slopes in the gorge section, high rainfall near the outlet and effects of the two large landslide features described earlier could also be responsible for greater sediment production in the lower watershed.

Seasonal hydrologic regime, abnormal hydrologic years, and seismic events affect sediment concentrations. However, the degree to which stream sediment concentrations reflect these factors will vary and should indicate denudation system behavior. For the Pacuare basin sediment concentration data, graphic analysis of sediment concentrations according to a rainy and dry season classification did not show any clustering of concentration according to season. There may be several factors working in opposite directions to confuse such an analysis. During the most humid months of the year, vegetation is greener, thicker, and occupies more surface area. During less humid months, vegetation is less robust. More soil is exposed to attack by rainfall -- which could give higher sediment loads. On the contrary, soils in the dry season have greater water holding capacity and might be less susceptible to the development of runoff and sediment entrainment. In the rainy season, soil pores are more likely to be full of water, making the basin more susceptible to saturation overland flow.

It was expected that the Bajo Pacuare gaging station would have higher sediment concentrations in the hydrologic years 1969 and 1970 due to abnormally high amounts of rainfall in those years. However, the sediment concentration--discharge relationship during this period is comparable to the entire period of record. Unfortunately, ICE collected only 25 samples during these two years, all during low flows. Thus, the sediment transport regime during years with abnormally high rainfall throughout the year remains poorly understood.

Higher concentrations might be expected for samples taken after earthquake events. Sediment concentrations plotted for two years after the 1983 Pérez Zeledón earthquake showed no clustering of data. These data also suffer from the same limitations discussed above. With few samples taken during high flows, it is difficult to infer the sediment transport regime during this period. Although no record of sediment concentrations at high flows exists for the period after the 1983 Pérez Zeledón earthquake, it is reasonable to assume that much greater quantities of sediment were carried out of the basin during high flows. The 0.29 km^2 of slopes denuded by the earthquake **(Figure 12)** plus unmeasured slope movement not seen on the aerial photos indicate that a large supply of sediment was available for transport. For example, the Río Boroi, indicated by the light colors along the channel in the aerial photo shown in **Figure 12**, is apparently choked with sediment.

Higher sediment concentrations would also be expected for the period after the 1991 Limón earthquake. **Figure 21** shows the extent of damage from the earthquake and the principal basins affected. The 100 km^2 affected area was changed from dense primary rainforest to bare soil by earthquake-triggered mass wasting (Vargas *et al.* 1995). The earthquake epicenter does not coincide with the area of greatest mass wasting. It has been suggested that the spatial pattern of mass wasting may be related to the location of faults (Chacón 1993, Vargas *et al.* 1995). Unfortunately, the river gage of the most affected basin, the Chirripó Atlántico, collapsed into the river during the earthquake.

A plot of sediment concentration data for samples collected before and following the April 1991 Limón earthquake shows a tendency for higher post-earthquake concentrations. **Figure 22** shows sediment rating curves plotted from sediment sample data collected before and after the Limón earthquake for the Pacuare, Barbilla, Estrella, and Telire watersheds. I calculated sediment loads using the pre- and post-earthquake rating curves to illustrate the magnitude of change in sediment load **(Table 16)**. For the two Pacuare stations, the rating curves were determined by the least squares method on logged data.

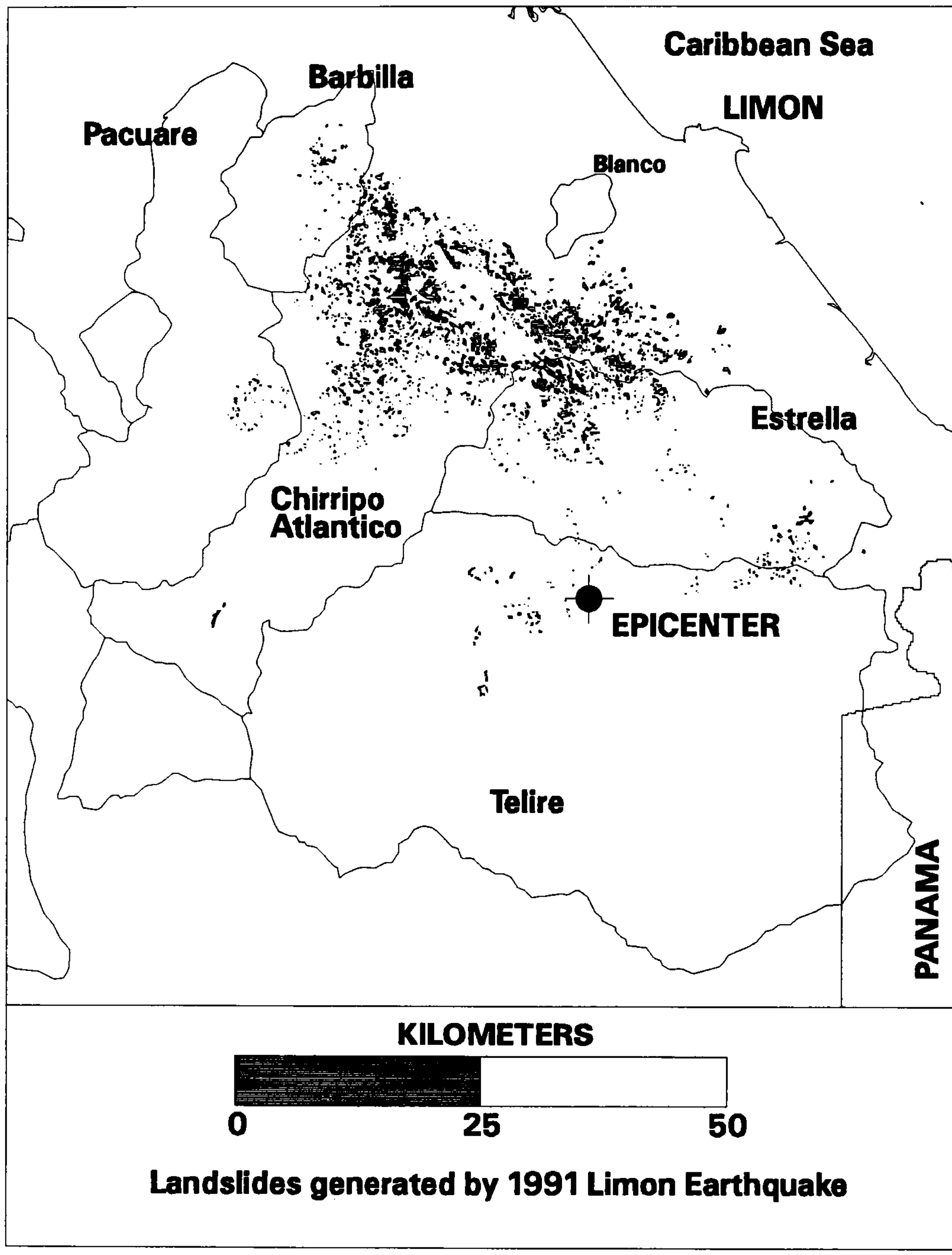

Figure 21. Location of landslides generated by the 1991 Limón earthquake

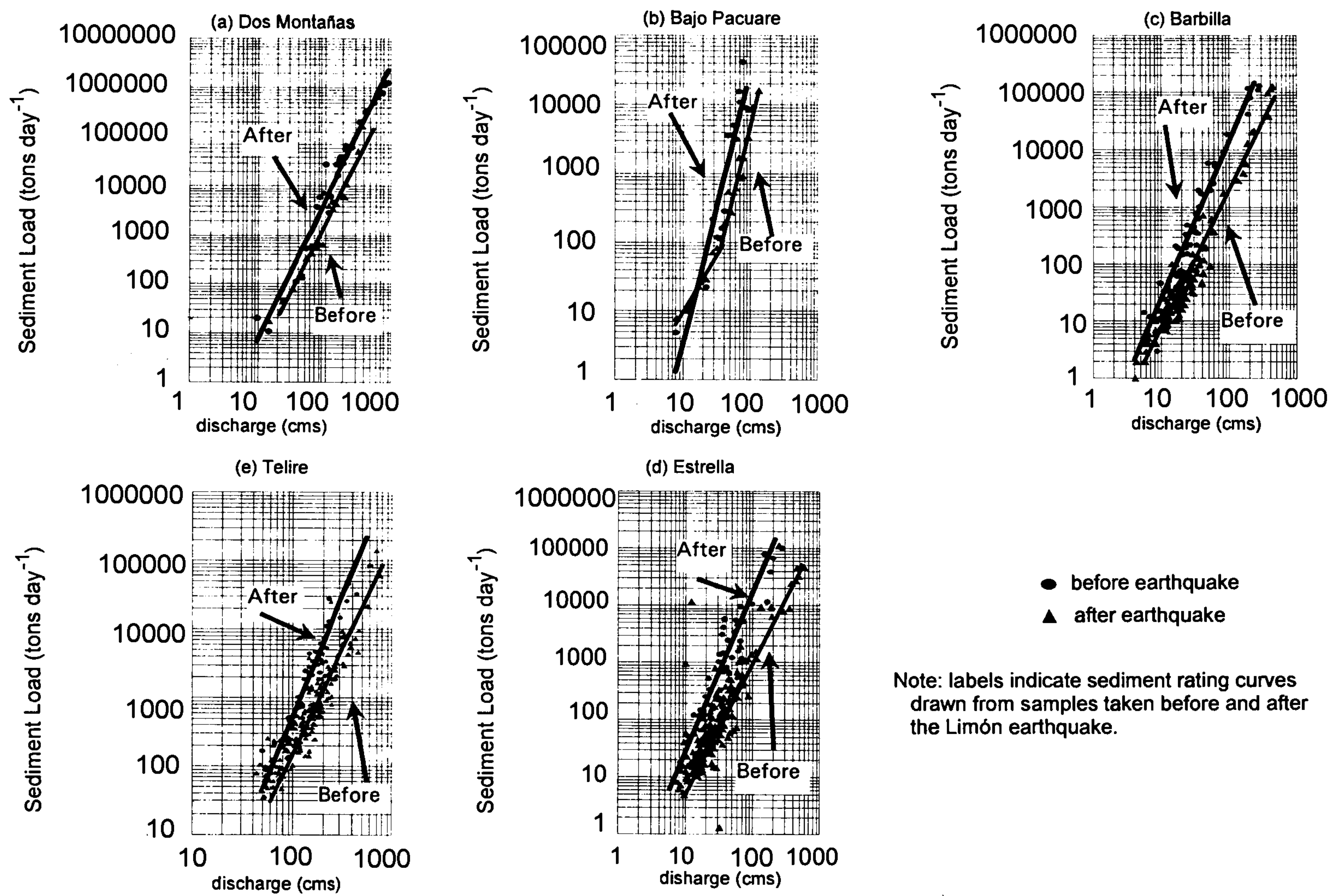

Figure 22. Sediment rating curves for samples taken before and after the Limón earthquake. (a) 651 km^2 Pacuare watershed above Dos Montañas, (b) 367 km^2 Upper Pacuare watershed above Bajo Pacuare, (c) 212 km^2 Barbilla watershed, (d) 2,120 km^2 Telire watershed, (e) 634 km^2 Estrella watershed.

Table 16. Sediment loads calculated using rating curves from before and after the 1991 Limon earthquake

Basin	Basin Area km^2	Area Affected by Landslides km^2	Sediment loads (millions of metric tons) Pre-earthquake Concentration data	Post-earthquake Concentration data	Magnitude Change
Pacuare (Dos Montañas) 1991	651	0.90	0.11	0.43	3.9
Pacuare (Dos Montañas) 1993	651	0.9	0.37	1.58	4.3
Pacuare (Bajo Pacuare) 1991	367	0.9	0.05	0.09	1.8
Pacuare (Bajo Pacuare) 1993	367	0.9	0.09	0.12	1.3
Barbilla 1991	212	1.63	0.28	1.19	4.2
Estrella 1991	634	15.50	3.26	16.91	5.2
Telire 1991	2129	2.50	2.14	10.25	4.8

Sediment concentrations and daily discharges were averaged according to discharge classes for the sediment load calculations. The method reduces the dampening of the regression curve due to greater numbers of samples taken at low discharges. Jansson and Rodriguez (1992) used this method for studies in the Upper Reventazón watershed. For the other three basins, the curves were fitted by eye and the sediment-discharge relation was determined graphically.

For both the Dos Montañas and Bajo Pacuare gaging stations, the position of the sediment rating curves are clearly higher for the post-earthquake data with respect to the pre-earthquake data. The sediment rating curves showed even greater upward displacement for the Barbilla, Estrella, and Telire drainage basins. Modelled differences in annual sediment loads of the Pacuare basin, using pre- and post-earthquake sediment curves for the hydrological years 1991/1992 and 1993/1994 further illustrates the effects of the earthquake.

The 1991 hydrological year was about an average year with respect to discharge and the 1993 hydrological year showed higher than normal discharge. For the Bajo Pacuare station, the post-earthquake sediment rating curves gives a sediment load between 1.3 and 1.8 times greater than that calculated using the pre-earthquake curves. The calculated sediment load is between 3.9 and 4.3 times greater for the post-earthquake data at the Dos Montañas station. In the other basins, the magnitude of change between pre- and post-earthquake sediment loads is similar to that of the Pacuare. The lower magnitude of change for the Bajo Pacuare station may have been due to the effect of a smaller number of sediment concentrations measured at the station.

The discussion above suggests that the channel system in the Río Pacuare watershed efficiently evacuates sediments from the basin. Nevertheless, the lack of quantitative data on the bedload fraction of total sediment load is a frequent limitation in our knowledge of sediment yield, and this limitation applies to the Río Pacuare as well. The abundance of bedrock banks, high drainage densities, and large boulders in the channel suggest that the sediment transfer system is limited by sediment supply rather than by the ability of the river to transport the sediment.

In summary, land cover and mass wasting appear to be important factors affecting the suspended sediment that leaves the basin. Over 1.5 times more suspended sediment per unit area originates in the lower watershed than in the upper watershed. Although the presence of steep slopes in the lower gorge could be important in explaining the greater quantities of sediment discharge at Dos Montañas, the contrast is probably due to land cover, being the major difference between the upper and lower watersheds. The effects of landslides triggered by the 1991 Limón earthquake roughly doubled the sediment load in the Río Pacuare watershed during the three years following the earthquake, injecting large pulses of sediment into the system.

7. SEDIMENT SOURCES AND MAGNITUDES

7.1. Introduction

In the previous chapters, I have discussed surface wash erosion, mass wasting, and channel processes, presenting some observations on the factors important in these processes in the Río Pacuare watershed. Briefly summarizing, I found surface wash processes to be highly variable. Deforested lands are likely to contribute at least twice as much sediment from surface wash processes as forested lands. Considerable bare ground is present in the rainforest, and sediment often accumulates where roots and organic litter are present. Erosion on cultivated lands often depends on land management of individual fields. Landslides generated by rainfall and earthquakes appear to be responsible for large quantities of sediment entering the transfer system. Sediment concentrations from before and after the Limón earthquake show the effects of landslides on the position of the sediment rating curve. Suspended sediment loads may be from two to five times greater following earthquakes that generate landslides.

The major sediment transfer processes can now be considered together in the context of the behavior of the sediment transfer system. In this chapter, I focus on the geographic distribution of processes, the frequency of processes, and the magnitudes of processes compared to each other, from a hillslope and watershed perspective and at a conceptual level. I include a discussion of the sediment source areas at the slope and watershed scales and estimate the importance of sediment sources in the watershed system. The discussion is separated into two parts. First, the question of where sediment source areas are located in the Pacuare basin is addressed, treating hillslope scale and watershed scale distributions separately. Second, the magnitude of processes in the context of the sediment transfer system is discussed.

7.2. Sediment Sources Areas in the Pacuare Basin

7.2.1. Slope Scale

Surface soil erosion at any point on a hillslope will depend on slope position, vegetation, soil properties, rainfall, and land management. Except for very small experimental watersheds, neither all the many possible combinations of soil erosion factors nor all points on a hillside can be taken into account. For example, most soil erosion studies do not account for unique hillslope conditions such as erosion occurring at field edges and on roads and trails (Harden 1992). In a tropical basin like the Pacuare, these difficulties are complicated by the great spatial and temporal variability of the factors considered.

Field observations discussed previously suggested that instead of within-field soil erosion, a large portion of the surface wash erosion occurring on slopes may be at field edges, stream banks, and on roads and trails. On typical fields of coffee and sugar cane, rill and gully systems are rarely observed. Rather, rills and gullies are often found near road cuts, on foot paths, or in special situations within the field. This condition may explain many of the high basin sediment yields reported (ICE 1993) compared to the low erosion rate values of many of the soil erosion plot studies reviewed in Chapter 5.

The land surface cover on individual slopes is an important factor in soil erosion because of the degree to which different land covers protect the soil surface. That the lower part of the Rio Pacuare basin contributes about one and a half times as much sediment per square kilometer as the forested upper basin suggests the importance of agricultural and pasture land covers in the generation of sediments.

Although there is uncertainty due to lack of long term data, my analysis of land cover and sediment yield relationships in the Pacuare basin indicates that land covers can be ranked according to their relative importance as sediment sources. Sugar cane appears to be the land cover most susceptible to erosion, according to sediment concentration and sediment trap data discussed in previous chapters. Although few data are available for coffee areas, they appear to rank second in magnitude as a sediment source in the Pacuare. Depending on land management practices such as weeding and use of mulch, coffee and sugar cane can sometimes be considered to be of equal importance as contributors to sediment transfer. Pasture lands are clearly less prone to erosion than cultivated lands. I observed many pastures with thick grass and very few visible signs of erosion. Forests are the least susceptible to soil erosion, but may be more erodible than some pastures.

Field observations support ranking forested lands and pasture lands as similar with respect to sediment generation. Several problems arise when comparing pastures with forests. Pasture lands are generally found on less steep slopes and vary greatly, depending on land cover management. Nevertheless, pasture grasses tend to provide excellent protection from falling raindrops. Even when runoff occurs, it may carry very few sediments because the grass holds the soil in place.

The soil surface is, in many places, open to attack in forested lands. My observations of surface soil erosion in forests in the Pacuare tend to confirm those of Ruxton (1967) in Northern Papua, New Guinea. Organic material on the forest floor breaks down rapidly due to abundant water and tropical temperatures, which support high biological activity. The dense tropical forest canopy prevents sunlight from reaching the forest floor, discouraging the growth of understory vegetation. Thus, the soil surface in tropical forests is open to attack from either direct rainfall or, in some cases, throughfall.

In addition to surface wash erosion processes, mass wasting on hillslopes was shown to contribute significantly to sediments moving in the watershed system. Landslide occurrence on hillsides depends on topographic position and other factors. At the hillslope scale, large landslides usually occur in hollows and on straight segments. Many small mass wasting processes are also occurring, but their spatial extent is highly variable. Landslides occurring in slope hollows are seen throughout the Pacuare drainage basin. The triggering of landslides, similar to runoff generation, often depends on the accumulation of water in the soil. For a small gently sloping area, runoff and soil erosion take place preferentially on saturated zones (e.g., Dunne and Black 1970a, Dunne and Black 1970b, Moore *et al.* 1976, Campbell 1985, Campbell 1992). In steeply sloping areas, the accumulation of water in saturation zones can lead not only to runoff generation, but to mass wasting as well (Kirkby 1987). The probability of occurrence of mass wasting is greater in these saturation zones because pore water pressure is greater. Pacuare area landslides occur where water accumulates in hollows. This is evident as one traverses a hillslope along a contour. It is in plan-concave slope segments that landslides are often found. Of course, this depends on the vertical as well as the horizonal slope dimension. Near ridge crests, landslides are less likely since there is a smaller up-slope area contributing moisture.

A relevant field example of the importance of saturation zones at the hillslope scale can be found along the road between Platanillo and Bajo Pacuare. There are numerous places along the plan concave portion of slopes where landsliding is evident. Near La Mina, a debris flow-type landslide occurred during the December 1993 storms (**Figure 16**). Downslope of the landslide contributing area, a colluvial deposit about 1 m thick covered the narrow valley bottom. Boulders near the surface and an unsorted vertical profile of the deposit indicate that the flow was highly viscous. Several months after the landslide occurred, perennial stream flow developed and incised the debris flow deposit. The stream now flows at the base of the deposit and just above the regolith - solid rock interface. This type of process is evident in other tributary streams of the Pacuare. Streams flowing on bedrock often expose a bank of unsorted boulders, cobbles, and finer sediments, indicating that the stream has cut through a mass wasting deposit.

The quantitative index of saturation zones, proposed by Beven and Kirkby (1982), could be a useful indicator of susceptibility to mass wasting in the Pacuare basin. Since the index accounts for water accumulation in surficial material, it indicates areas of increased pore water pressure in the soil, an important factor in the triggering of landslides (Everett 1979). The topographic index (TI) incorporates the effects of slope angle and runoff contributing area for a location in a watershed:

$$TI = \ln(A/\tan B)$$

where A is the upstream contributing area and B is the slope angle. The topographic index is the natural logarithm of the ratio of upstream contributing area to the tangent of slope angle. Considering the effect of different values for the equation and their physical basis, larger values of the index occur in areas where water accumulates and lower values in areas that do not hold water. Steeper slopes increase the denominator and decrease the index number. Water in soils on steep slopes tends to drain downslope due to gravitational forces. The contributing area parameter accounts for the effect of drainage area to a point on the landscape. Large contributing areas increase the numerator and the index number. Landslides are more likely to occur where water concentrates in hollows, hence, increasing pore water pressure. There must also be sufficient slope steepness for landslides to occur. Some combination of slope steepness and water accumulation potential should provide an ideal setting for the occurrence of landslides.

Figure 23 is a map of the topographic index with superimposed contour lines for the La Mina site described in Chapter 5. I calculated the digital map layer using map algebra applied to the 50 m grid cell digital elevation model. On ridge crests, topographic index numbers are less than three, indicating points with little or no upstream drainage area. Intermittent and perennial stream channels have values greater than 11, reflecting gently sloping channels with

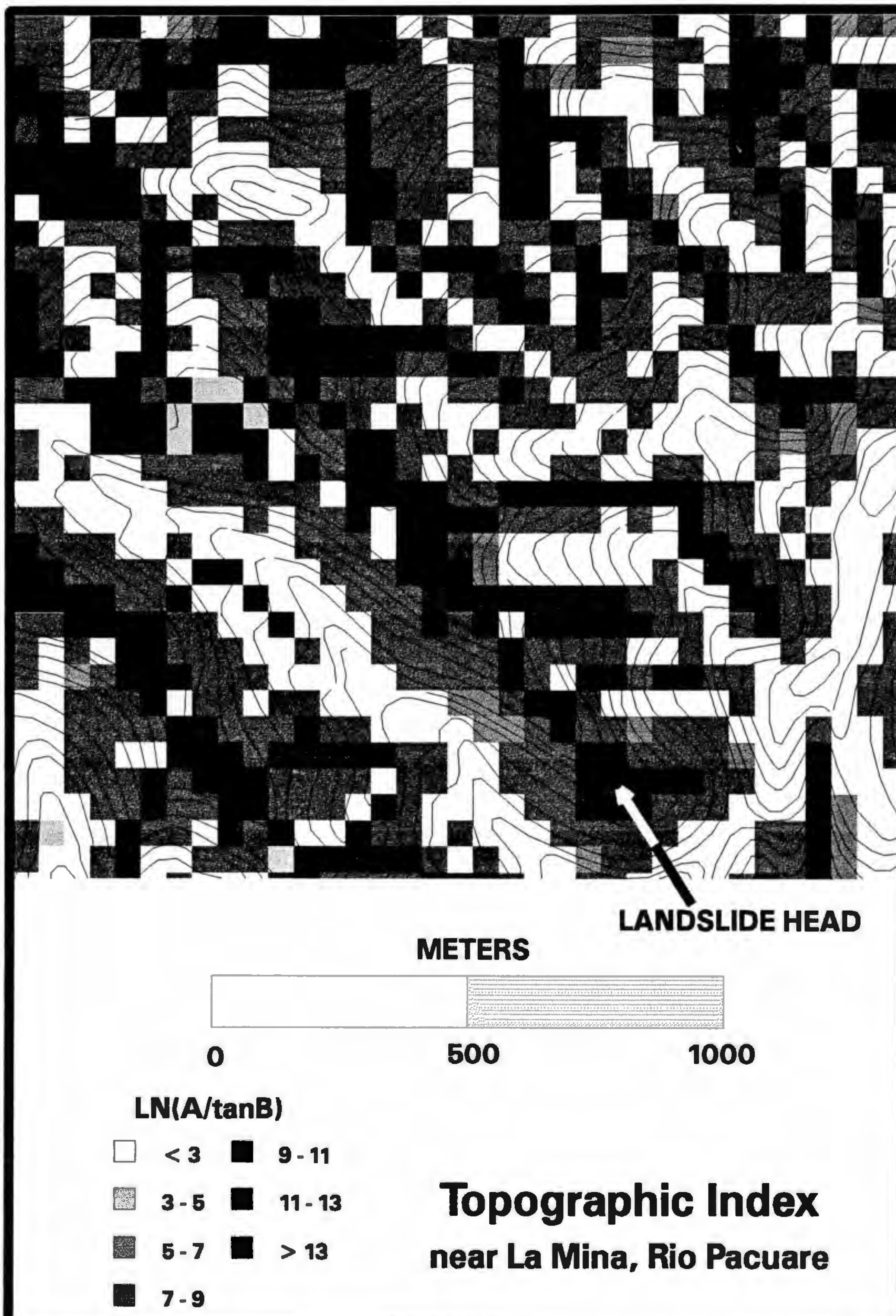

Figure 23. The topographic index near La Mina

large upstream drainage area. These areas collect sufficient water to transport sediments by channel flow. Topographic index values between three and nine characterize the middle and lower portions of slopes. It appears as though topographic index values between nine and 11, such as the area of the landslide head in **Figure 23**, represent critical potential saturation in steep areas.

At the landslide head, where the La Mina landslide originated, slopes are both longitudinal- and plan-concave. These sites are ideal for water accumulation. It is apparent that the combination of saturation zone and steepness provided an unstable slope environment in this case. Zones of slope instability move upvalley after a landslide such as the one at La Mina because the soil in the hollow has been evacuated. I observed hillslope hollows with landslide scars throughout the Pacuare basin and believe these features indicate the importance of mass wasting in saturation zones as a significant sediment-generating process. I was unable to develop a quantitative experiment to test the relationship between the topographic index and the occurrence of landslides because locating landslides in the field and matching them to the DEM proved too difficult. However, saturation zone landslides occur throughout the Pacuare landscape and appear to be important in the overall slope evolution of this area.

Landslides occurring on straight slope segments are generated by heavy rainfall and are triggered by earthquakes. They tend to be associated with the steepest slopes. Evidence of these landslides is found throughout the drainage basin. They frequently create forest gaps. **Figure 24** shows a typical rainforest gap created by a landslide near the Quebrada Terciopelo. The landslide removed soil material down to the bedrock, exposing the soil profile on both sides of the

A

B

Figure 24. Forest gaps created by mass wasting on steep slopes. (a) view looking upslope into gap caused by mass wasting (b) bedrock exposed after mass wasting, note exposed soil profile.

landslide scar. As one traverses this hillslope, and others in steep forested areas, these gaps and their associated landslide scars can be seen every 200 or 300 m. Slope evolution at these sites appears to conform to the landslip regolith cycle (Young and Young 1974). Weathered bedrock develops into a soil profile over time. The soil reaches a critical thickness at which it is subject to instability. Rainfall or earthquakes provide the triggering mechanism for slope failure. The cycle is repeated as the slope retreats over long periods of time.

Hillslope sediment transfer is thus characterized by accelerated surface wash processes on bare soil. Most bare soil is found on agricultural land covers, but forested lands exhibit significant bare soil under the canopy. Mass wasting at the hillslope scale occurs in saturated zones and on steep straight segments where a sufficiently thick soil profile has developed.

7.2.2 Watershed Scale

Differential soil erosion can be expected to occur over large areas at the watershed scale, as well as at different points on a hillslope. Some parts of the Pacuare watershed contribute more sediment than other areas, due to differences in rainfall, topography, soils, seismic activity and land cover. The environmental conditions, previous research, and field observations discussed in previous chapters suggest the following areas within the Pacuare basin as important source areas of surface wash erosion (**Figure 25**):

(a) cultivated lands. Sediment concentrations measured in tributary streams were the highest in the sub-basins draining coffee and sugar cane areas.

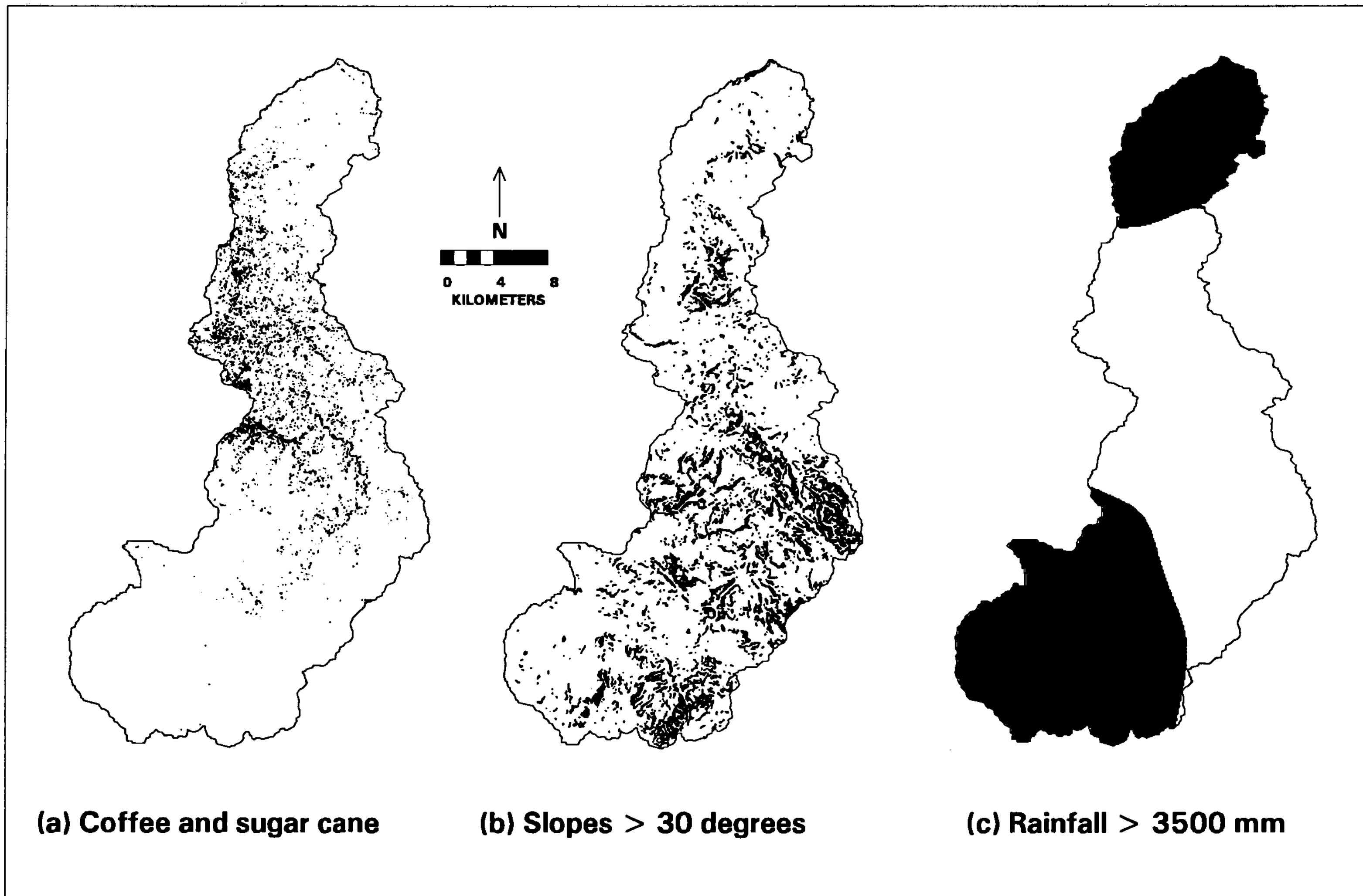

Figure 25. Areas of high susceptibility to surface wash erosion. (a) coffee and sugar cane cultivation, (b) slopes greater than 30 degrees, (c) rainfall greater than 3500 mm.

Although ground cover is variable, depending on land management and period of the crop cycle, these land covers are most susceptible to direct rainfall.

(b) slopes over 30 degrees in rainforest. The great majority of slopes over 30 degrees are in rainforest. These occur along the gorge section of the lower watershed and in several concentrations in the upper watershed. Poor ground cover on the forest floor offers little protection to soil surfaces. Steep slopes increase the velocity of surface runoff and encourage progressive downslope movement of soil by splash erosion.

(c) the two areas with highest rainfall. Near the Cuencas rain gage in the southwestern section and the Finca Mirador rain gage in the northeastern section of the watershed, the average annual rainfall is over 1.5 times greater than in the middle section of the watershed. More rainfall increases the likelihood of overland flow and sediment entrainment. However, my field observations in these two zones suggested they are similar to other areas in the watershed, and that even high amounts of annual rainfall may not be sufficient to generate commensurate high levels of surface runoff. For example, near the Río Simari and Cerro Mirador in the southwestern section of the Pacuare basin, soil surface conditions on hillslopes are very much like those found in other forested areas of the basin. I found no evidence of rill and gully development or deposition at the base of slopes that would indicate increased soil erosion in these sections. My suggestion that increased soil erosion is due to greater precipitation in these areas is based on speculation more than field evidence. Clearly, more study is needed in these areas.

Note that these three factors important for surface wash erosion generally do not occur together. Cultivation occurs on the less steep slopes in the area of lowest rainfall. The two areas of highest rainfall do not have the greatest concentrations of steep slopes and cultivation. Except for some areas in the lower river gorge section and the southernmost upper watershed, steep slopes occur in neither the highest rainfall zone nor cultivated areas. Therefore, the differences in surface wash erosion from one part of the basin to another may be less pronounced than might be expected.

At the scale of the entire Pacuare basin, landslides are most likely to occur in association with fault scarps, river gorges, and other steeply sloping areas. **Figure 26** is a map showing areas most susceptible to landslides. The map shows slopes over 35 degrees and sites where landslides have been observed. Steeply sloping areas coincide with geological faults. In addition to the influence of slope steepness, there could be a relationship between faults and landslides due to greater earth shaking in fault zones compared to non-fault zones. (Chac6n 1993, Vargas *et al.* 1995). Cervantes (1989) mapped several landslides coinciding with a fault terminating at Dos Montañas. Miocene crater walls, due to their steep slopes, appear to have suitable conditions for the development of landslides.

My field observations in the Río Pacuare watershed confirm the general appearance of the map in **Figure 26**. Observers traveling the main stem of the

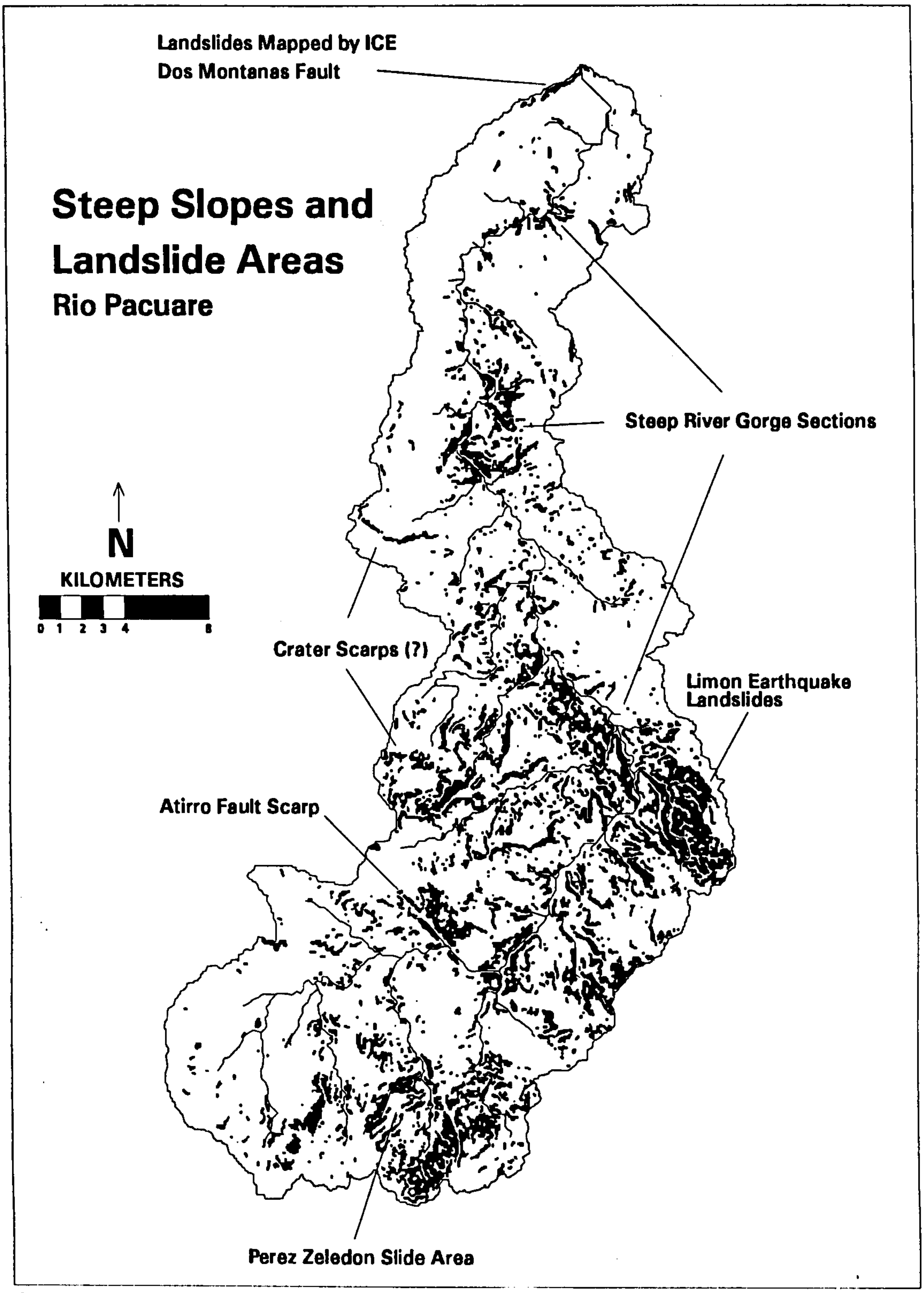

Figure 26. Steep slopes and landslide areas of the Río Pacuare watershed. The shaded areas are slopes greater than 35 degrees, as measured from the digital elevation model. Also noted are areas where landslides have been observed.

river by boat will notice the numerous landslide scars found in the river gorges. Near the watershed outlet, they will see the landslides along the fault scarp mapped by Cervantes (1989) on the left bank. Traveling overland between Tayutic and Bajo Pacuare, one will notice the landslides along the Jicotea fault scarp. From the town of Pacayitas, looking to the south and east, landslide scars are clearly visible along the crater wall mapped by Bergoeing and Malavassi (1982). In the absence of rigorous statistical analysis suggesting slope angle thresholds for landslides, the 35 percent figure (as measured from the DEM) agrees very well with observed landslides and landslide scars. Areas with more gentle slopes, such as the northwestern watershed divide and to the southeast of Cerro Mirador, have very little evidence of landslides and landslide scars.

In summary, surface wash erosion processes are not very different from one part of the basin to another. Because the areas of highest rainfall, cultivation, and steep slopes do not occur together, there is no extreme spatial concentration of environmental factors leading to surface wash erosion. The major sediment source areas are cultivated lands, but sediments also originate in forests. Mass wasting processes are associated with steep slopes in river gorges, geological faults, Miocene crater walls, and the energy dynamics and epicenter location of a given earthquake. With respect to sediment yield at the basin outlet, the spatial distribution of processes in the Pacuare basin appears to be less critical for understanding the sediment transfer system than the temporal distribution, magnitude and frequency of processes.

7.3 Magnitude of Sediment-generation Processes: Contributions of the Different Sediment Sources

One goal of this study was to evaluate the importance of different sediment transfer processes in the context of the watershed system. Due to difficulties of measurement and lack of resources, all the relevant processes could not be studied. However, it is possible to suggest the range of values for the major sediment transfer processes in the Pacuare basin. **Table 17** lists soil erosion, mass wasting, and sediment yield estimates for the Pacuare basin. The table is intended to show probable scenarios of sediment transfer processes rather than a detailed sediment budget. For a basin as large as the Pacuare watershed, it is unlikely that a detailed sediment budget could ever be developed. The table is a semi-empirical model of approximate sediment budget scenarios, based on field data and reasonable estimates of unmeasured processes.

Three mass wasting and soil erosion scenarios for annual periods are suggested in these scenarios, which are portrayed graphically in **Figure 27**. Comparatively little soil erosion and mass wasting occur during years with less than average rainfall and no high-magnitude seismic activity (Scenario A). Years with less rainfall but mass wasting triggered by earthquakes make up an intermediate scenario (Scenario B). Years with significant erosion-producing storms usually occur together with widespread mass wasting (Scenario C). A fourth scenario, not listed here, would occur if massive earthquake-generated landslides occurred together with heavy storms. This condition has not occurred in recorded history of the Pacuare watershed, but could be similar to the

Table 17. Annual Sediment Budget Scenarios for the Río Pacuare

Component	Source	Erosion rate tons km^{-2} yr^{-1}	Sediment tons
A. LOW MASS WASTING - LOW SOIL EROSION SCENARIO			
Soil Erosion*			
Forest (448 km^2)	estimated at 25% of coffee	18	8064
Secondary Forest (84 km^2)	estimated at 25% of coffee	18	1512
Coffee (30 km^2)	Bermudez 1980	73	2190
Sugar Cane (14 km^2)	estimate	20	280
Pasture (65 km^2)	Vahrson and Cervantes 1991	37	2405
Clouds and Shadows (10 km^2)	estimate	18	180
Total Surface Wash Erosion			14631
Mass Wasting** estimated			
1 landslide km^2 yr^{-1}(100 m^3 km^2 yr^{-1})	estimate	150	97650
Total Gross Erosion			112281
Suspended Sediment Yield***	ICE minimum		142818
Bedload****	estimated at10% of suspended load		14281
Total Sediment Yield			157099
Residual			44818
B. INTERMEDIATE MASS WASTING - LOW SOIL EROSION SCENARIO			
Surface wash erosion (same as in scenario A)			14631
Mass Wasting estimated			
1 landslide km yr^{-1}(500 m^3 km^2 yr^{-1})	estimate	750	488250
Total Gross Erosion			502881
Suspended Sediment Yield	my calculation 1991		433000
Bedload	estimated at10% of suspended load		43300
Total Sediment Yield			476300
Storage			26581
C. HIGH MASS WASTING - HIGH SOIL EROSION SCENARIO			
Soil Erosion			
Forest (448 km^2)	estimated at 25% of coffee	725	324800
Secondary Forest (84 km^2)	estimated at 25% of coffee	725	60900
Coffee (30 km^2)	Romero 1991	2900	87000
Sugar Cane (14 km^2)	Romero 1991	2900	40600
Pasture (65 km^2)	Berru 1980	269	17485
Clouds and Shadows (10 km^2)	estimate	725	7250
Total Surface Wash Erosion			538035
Mass Wasting estimated			
1 landslide km^2 yr^{-1}(1000 m^3 km^2 yr^{-1})		1500	976500
Total Gross Erosion			1514535
Suspended Sediment Yield	my calculation 1993		1580000
Bedload	estimated at 10% of suspended load		158000
Total Sediment Yield			1738000
Residual			223465

* soil erosion values taken from Table 8 and from published sources
** landslide assumed depth of one meter and bulk density of 1.5 g cc^{-1}
***suspended sediment yield is reported by ICE(1993) and corrected by 25% to account for underestimation of daily data
**** bedload is calculated as 10 percent of suspended sediment load

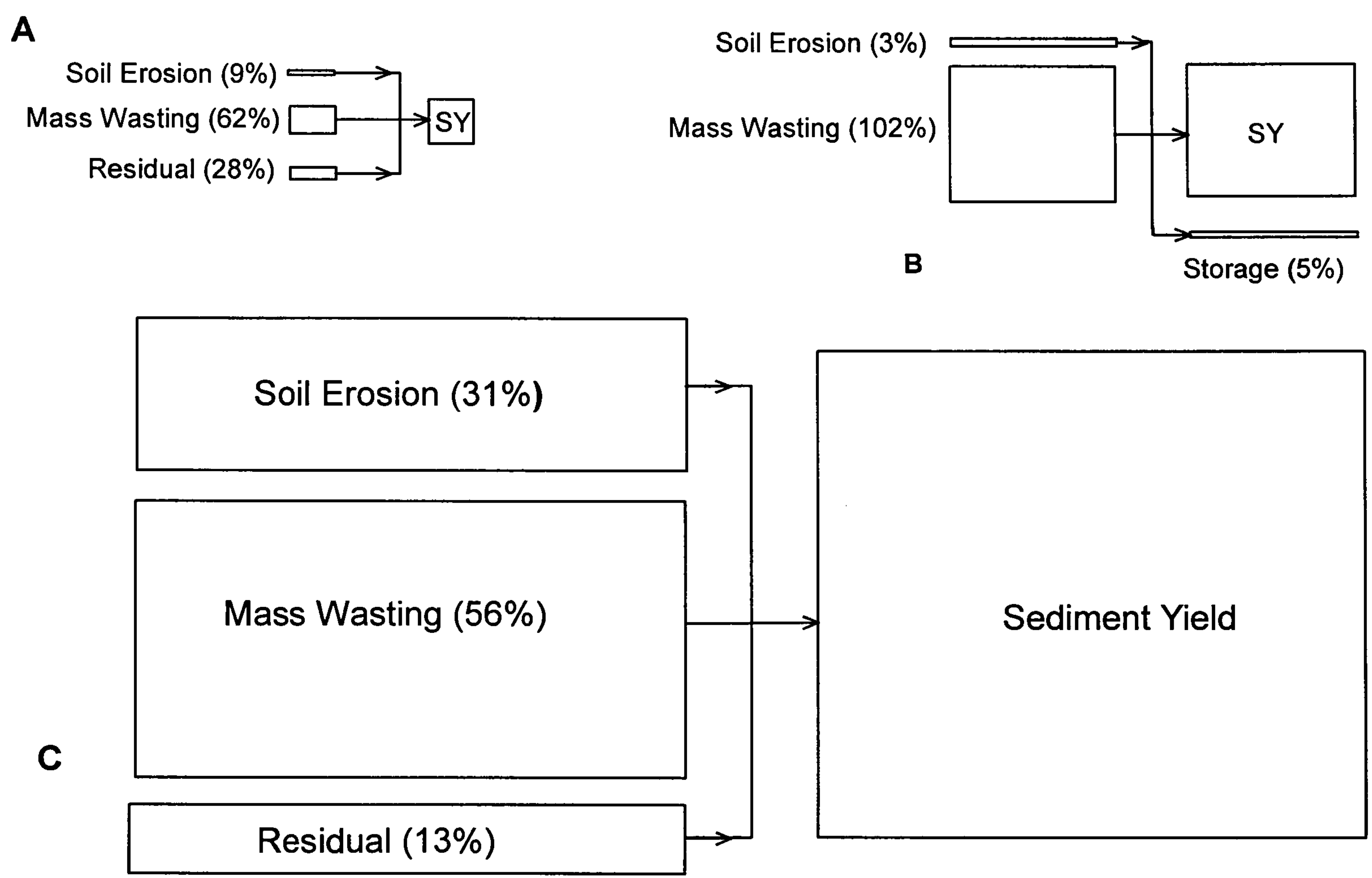

Figure 27. Sediment budget scenarios for Río Pacuare watershed. Vertical height of boxes equivalent to magnitudes of sediment from Table 17.

conditions in the adjacent Río Chirripó Atlántico, where 50 km^2 of forested lands were denuded by the 1991 Limón earthquake.

The scenarios in **Table 17** suggest climatic and seismic conditions commonly found in the Pacuare drainage basin and the magnitude of sediment transfer processes related to those conditions. By assigning sediment transfer process rates from available data and estimates, I show probable sediment-transfer scenarios on an empirical basis.

I assigned soil erosion rates from regional agricultural plot data presented in **Table 8** and made estimates for land uses, including forests, for which no data are available. Erosion on forested lands can be estimated on the basis of suspended sediment records (**Table 15**), which show the lower Pacuare watershed generally yielding about 50 percent more sediment per unit area than the forested upper watershed (ICE 1993). Since about half of the lower watershed has been cleared, it can be assumed that the increase in sediment yield per unit area is a function of land cover. Twice as much surface wash erosion on cleared lands than on forested lands would account for the 50 percent increase in sediment yield per unit area for the lower watershed. Thus, surface wash erosion rates on forested lands could be estimated as one half of the rate on cleared lands. However, I chose a value for surface wash erosion on forested lands of 25 percent of the rate on cleared lands to incorporate both sediment yield data and locally-based understandings of the relationships between erosion rates on forested and cleared lands (Jansson and Rodriguez 1992). Based on soil erosion plot studies reviewed in Chapter 4, the low soil erosion scenario is representative of most of the studies carried out in the nearby

Turrialba area. The high soil erosion scenario corresponds to the highest values in **Table 8**, which are more representative of the effects of low frequency - high magnitude storm events.

The landslide data in **Table 17** are based on very rough estimates of landslide density and area. However, they are in the range of values measured from remote sensing data discussed in Chapter 5, and field observations suggest they are conservative. I estimated a depth of 1 m for calculating the volume of sediment delivered to channels by landslides. Vahrson and Hernandez (1992) estimated an average depth of 3 m for landslides triggered by the Limón earthquake. Landslide material varies in depth, but 1 m seems to be a conservative average figure.

My figures do not take account of landslide-generated sediment going into storage, but field observations, remote sensing imagery, and other studies on landslides in this area (Vahrson and Hernandez 1992, Chacón 1993, Mora and Mora 1994) suggest that most landslide material is delivered to stream channels. Landslide deposits lying near channels are often swept into the channel system by high flows or eroded by falling rain. It is likely that within a year, landslide-generated sediments not deposited in the channel initially will enter the channel. Given the uncertainty about the percentage of landslide sediments that enter the channel and the conservative value I used to represent landslide depth, I chose to exclude estimations of colluvial sediment storage.

A specific gravity of 1.5 g cc^{-1} was used to calculate the weight of sediment moved by mass wasting. The value 1.5 g cc^{-1} was chosen because values of 1.2 to 1.5 g cc^{-1} are common bulk densities for soil material in the

Turrialba area (Kass 1994) and the landslide material usually includes slightly denser weathered bedrock.

I estimated sediment transfer to be 100 m^3 km^{-2} yr^{-1} for the low mass wasting scenario (A). This estimate should be viewed with caution because there is a lack of data on landslides during years with few sediment-triggering events. However, the estimate for sediment transfer from landslides in this scenario is about 20 percent of the sediment measured from remote sensing data for the Pérez Zeledón earthquake in the Pacuare watershed. That earthquake, with epicenter well outside the watershed, triggered about 25 landslides. Therefore, the smaller landslides, representing a volume of 100 m^3 km^{-2} yr^{-1}, appear reasonable. I chose an erosion rate of 500 m^3 km^{-2} yr^{-1} for the intermediate mass wasting scenario (B), a value higher than the 440 m^3 km^{-2} yr^{-1} mass wasting erosion from the Pérez Zeledón earthquake in the Pacuare watershed (**Figure 12**). The estimate of 1000 m^3 km^{-2} yr^{-1} for the high mass wasting scenario (C) is 70 percent of the erosion triggered by mass wasting from the Limón earthquake.

Sediment yield data taken from the ICE (1993) sediment bulletin for the low mass wasting - low soil erosion scenario are the minimum for the period of record. I then increased by 25 percent the Pacuare data shown in the table, a correction in line with studies in the Reventazón watershed showing that calculations based on daily discharges underestimated sediment load by 25 percent when compared to hourly data (Jansson and Rodriguez 1992). Finally, I estimated bedload at 10 percent of suspended load to calculate the figures in **Table 17.** I selected the 10 percent figure because it is often used in calculating sediment load and falls on the conservative side (Dunne and Leopold 1978). The

10 percent figure is very likely an underestimate considering the size of bed material in the channel. Another study in a steep tropical watershed showed much higher figures (Simon and Guzman-Ríos 1990).

I did not account for channel storage in **Table 17** for several reasons. High drainage density, the ubiquity of bedrock channel bottoms and banks, and the lack of floodplains in the watershed suggest that sediment transport is supply-limited. Channel storage is most important in watersheds where total gross erosion exceeds the conveyance capacity of a river to export the sediment supply (Trimble 1983).

Between-field soil erosion is also lacking in the data presented in **Table 17**, but is likely to be an important sediment budget component in the Pacuare region. These sediment sources include roads, trails, and the many micro-topographic areas where bare soil is susceptible to rainfall attack. Dunne (1979) and Harden (1992) pointed out the importance of roads and trails as sediment sources. For the entire 651 km^2 Río Pacuare watershed, the overall soil erosion from roads and trails is not likely to be great because the density of the network is low. Some roads are composed of river cobbles that act to armour the road surface and others are vegetated. Like agricultural land covers, roads and trails are also variable in their surface conditions. Perhaps more important to the sediment transfer system are small areas where bare soil is open to attack such as road cuts, boundaries between fields and ditches or trails, mass wasting features less than 1 m^2, and other similar areas. These areas and their contribution to sediment transfer represent perhaps the least known aspect of sediment budgets. Their presence, or lack thereof, must be acknowledged in sediment budget studies.

Table 17 shows that sediment yield at the basin outlet is greater than gross erosion by surface wash on slopes. Under the low erosion scenario, gross erosion is about seven percent of the minimum sediment yield and three percent of the average sediment yield for the period of record (ICE 1993). Even under the high erosion scenario, the amount of sediment transferred to channels by surface wash erosion processes is only 1.3 times the average watershed sediment yield, and about a third of the maximum watershed sediment yield. These figures contrast sharply with many studies of erosion and sediment yield in temperate climates (e.g., Trimble 1975, Morgan 1986) and in tropical climates (Douglas 1969), which generally show that surface wash erosion is five to 20 times greater than sediment yield. I attribute the differences to mass wasting contributions, lack of storage opportunities, high sediment transport efficiency, and to the processes not considered, such as channel bank erosion and between-field erosion. Given the possible underestimation of sediment yield values, it is clear that processes other than surface wash erosion are contributing a large proportion of the sediment leaving the basin.

Table 17 includes estimates of sediment transfer from landslides in the Pacuare basin. The estimated values show how a rapid event can produce one to two times the sediment that is typically flushed from the basin during a year. The short travel distance between hillslope and channel (high drainage density) means that sediments mobilized by landslides are quickly evacuated from the Pacuare basin. The landslide-based sediment transfer could have been much greater if epicenters or the energy focus from the two recent events had been closer to the Pacuare watershed. In the case of the Limón earthquake, the extent of mass wasting processes and their effect on sediment movement in the watershed would have been much greater had the earthquake occurred during the rainy season, when soils are saturated, instead of at the end of the dry season.

Table 17 also shows some rough estimates of landslide frequency and volume. If, in one year, one landslide that was 20 by 25 meters in area occurred in each square kilometer in the entire basin, the amount of sediment transferred to the river channel by landslides would approximate the average annual sediment load of the Pacuare river. This hypothetical scenario points out how relatively small areas of landsliding can mobilize great quantities of sediment.

In summary, the data suggest that surface wash erosion processes on fields and slopes in the Pacuare basin contribute less sediment than the combination of mass wasting, channel, and between-field erosion processes. Even under the high erosion scenario, gross erosion values are close to average sediment yield values. By triggering mass wasting, earthquake events can indirectly mobilize large quantities of sediments. Even using conservative hypothetical estimates of landslide density, the data suggest that mass wasting is probably responsible for a large portion of the sediment leaving the basin. Sediment yields may be underestimated due to lack of sediment concentration measurements at high discharges. In the neighboring Reventazón basin, sediment loads were found to be considerably higher when turbidimeter data were used to model high discharges (Jansson and Rodriguez 1992). If landslide sediment mobilization is equivalent to 2,000 $m^3\ km^{-2}\ yr^{-1}$, mass wasting contributions to the sediment budget would be roughly equivalent to average sediment loads.

8. CONCLUSION

8.1 Land Use and Sediment Yield

Although it is commonly accepted that vegetative cover is the most important factor in soil erosion and sediment yield in the tropics (Dunne 1979, Stocking 1988, Lal 1990), the results of this study in the steep humid tropics of Costa Rica suggest that this relationship is weaker than might be expected. A multivariate analysis of sediment yields from 18 watersheds showed no statistically significant relationships between sediment loads and commonly recognized erosion-controlling factors. Based on reported sediment loads for the Pacuare drainage basin, cleared lands contribute about twice as much sediment as forested lands. Coffee and sugar cane fields are important sediment sources, but occupy only a small part of the Pacuare drainage basin. Instead of the factor of 10 difference in sediment yield commonly reported for agricultural versus forested basins (Douglas 1969, Douglas 1970, see Morgan 1986 for review) the Talamanca watersheds examined in this study have differences of about a factor of two. Even heavily forested watersheds have high sediment yields.

The differences in sediment behavior between most previously studied watersheds and the Costa Rican watersheds reported here can largely be attributed to mass wasting on steep slopes in the forested Costa Rican basins. This study also indicates that considerable wash erosion is occurring in the mountainous rainforests. Tropical rainforests on steep slopes, then, do not appear to efficiently protect the soil as expected. Although land use is an important control of sediment yield, it acts in combination with the triggering effects of extreme rainfall and earthquakes on mass wasting.

8.2 The Role of Mass Wasting in Sediment Transfer in Costa Rica

While the importance of landslides in Costa Rica have been recognized, this is the first study to examine the magnitude and frequency of mass wasting and its implications for basin denudation. Landslides generated by earthquakes occur on the steepest slopes, often coincident with the location of geological faults and river gorges. Regolith to a depth of 1 to 3 m moves downslope -- most of it to the stream channel. Given high drainage densities and steep channel gradients in this region, channel networks are effective in delivering sediment to the basin outlet. Whether earthquakes occur in the wet or dry season can be critical with respect to the quantity of sediment mobilized. Remote sensing and field estimates for three landslide-triggering events show that instantaneous sediment mobilized in the Pacuare basin was as much as, or a significant percentage of, the total suspended sediment evacuated from the watershed in a typical year. Thus, it is clear that these events are of sufficient magnitude to be important in the overall sediment transfer of the region.

In the humid tropical mountains of Costa Rica, earthquake and rainfall events are frequent enough to provide an almost constant supply of sediment to the watershed system. Some landslides triggered by rainfall occur in almost every year. During years with large storms, numerous landslides mobilize great quantities of sediment. The December, 1993, storm in the Pacuare basin, which produced numerous landslides near Jicotea, had a recurrence interval of about 5 years. Moderate intensity, high magnitude rainfall associated with cold fronts from the northern mid-latitudes appears to play an important role in sediment transfer. These long duration storms can fill soil layers with water, generating saturation overland flow and landslides on steep slopes. Earthquakes of magnitude 5.0 or greater generate landslides and these occur, on average, every 5 to 10 years. Because recurrence intervals for sediment-mobilizing earthquakes are about 6 years and those for rain storms are about five years, such events result in pulses of sediment injected into the watershed system approximately three to four times each decade.

Geomorphologists have noted the importance of mass wasting in long-term slope erosion, reasoning that periodic landslides provide a sediment supply for decades or centuries (Pain and Bowler 1973, Pearce and Watson 1986, Keefer 1994). The importance of mass wasting in short-term slope erosion (over periods of less than a decade) has not been previously recognized. Because return intervals of mass wasting processes that mobilize and evacuate sediments in the Pacuare watershed are relatively short, the role of mass wasting in short-term slope erosion must be acknowledged.

8.3 Sediment Balance

Although a detailed sediment budget could not be developed, an approximate accounting of sediment processes for the Rio Pacuare watershed shows that surface wash erosion can only provide a small portion of the sediment that leaves the basin. Mass wasting processes may account for well over half the sediment discharge from the basin. Other processes that were not accounted for, but when accumulated may be important, are channel bank erosion, erosion on roads and trails, and between-field soil erosion.

The sediment dynamics of the watersheds on the Atlantic slope of the Cordillera de Talamanca changed dramatically after the 1991 Limón earthquake. Sediment rating curves drawn for conditions before and after the earthquake show that sediment yield at low discharges does not differ greatly between the two periods. At high discharges, however, the post-earthquake sediment rating curve is substantially higher. Calculations of sediment discharge based on sediment rating curves derived from pre- and post-earthquake data indicate that sediment loads in the years following the earthquake almost doubled in the upper Pacuare basin. The simulated sediment loads for the entire 651 km^2 Pacuare basin quadrupled for the period after the earthquake. The post-earthquake increases in sediment concentration at a given discharge took place in one of the Talamanca basins least affected by the earthquake, which suggests that lower magnitude earthquakes occurring closer to the watershed could produce similar changes. Post-earthquake sediment loads in other basins on the Atlantic slope of the Talamancas may have been as much as five times greater (**Table 16**).

Several different combinations of environmental conditions determine the dynamics of the sediment transfer system in the Río Pacuare watershed and adjacent basins. In years with few or no large, long-duration storms nor high-magnitude seismic activity, sediment transfer processes are of comparatively small magnitude. These conditions result in the minimum sediment yields reported for this area. The volume of sediment delivered to the channel may double when earthquake-triggered mass wasting occurs in a year without considerable sediment-generating storms. The 1991 hydrologic year in the Río

Pacuare watershed appears to reflect this condition. Sediment discharge may be as much as five times greater during years in which seismic activity and multiple sediment-producing storms occur. The 1993 hydrological year reflects such conditions. The combination of precipitation and seismic regimes is thus an important determinant of the overall sediment transfer system.

8.4 Implications

In the Cordillera de Talamanca of Costa Rica, the presence of natural forest cover does not have the protecting effect that is commonly attributed to forest cover throughout the world. While natural forests do give better protection against erosion than cultivated fields, leaving a watershed in its natural state cannot be assumed to greatly reduce sediment yield in this area. In contrast to transport-limited sediment transfer systems (e.g., Trimble 1983), the steep humid tropics of Costa Rica is a supply-limited system. It follows that upstream soil conservation measures could reduce sediment yields. However, since the largest inputs to the sediment system are from mass wasting events with a three-year return period, on-farm soil erosion control is not likely to provide great benefits in reducing downstream sediment yield. Soil conservation should rather be employed to maintain soil productivity, thereby reducing pressure to clear forests.

I have shown that sediment concentrations in the Pacuare and nearby rivers increased substantially after the 1991 Limón earthquake. A sediment rating curve based on concentration data for the entire period of record may overestimate loads during periods of greater slope stability and underestimate loads after earthquakes or extreme rainfall events. Predictions of sedimentation for engineering purposes may not account for processes with recurrence intervals outside the period of measurement. Engineering projects must consider the probabilities of such events, although the period of environmental monitoring in the region is very short. Clearly, sediment loads for this region must be reported and interpreted with caution.

8.5 Directions for Future Research

In the past, much emphasis has been placed on the Hortonian overland flow model and soil erosion models like the USLE that reflect the importance of rainfall intensity. Since most storms in the tropics are normally of short duration and high intensity, many workers may have over-emphasized rainfall intensity, without placing equal attention on the high infiltration capacities of some tropical soils. This study suggests saturation overland flow is important in generating runoff. Future soil erosion research in the tropics should place more attention on the saturation overland flow model of runoff. Studies using large collectors at the bottom of hillslopes, similar to the well known experiments of Dunne and Black (1970a and 1970b), would be instructive.

In environments subject to mass wasting, the relationship between runoff and sediment yield is weakened because landslides are not strongly related to storms and runoff. Although pulses of concentrated sediment during periods of low runoff have been recognized (Butler and Malanson 1996), they should receive further research attention as they create a key difference between sediment transfer systems in areas susceptible to landslides and other areas.

Scale problems and the use of GIS and remote sensing, as they are applied to sediment transfer studies, deserve closer attention. Extrapolation between scales is a common practice, but has received less attention with regard to its validity. The spatial resolution of environmental data for developing sediment budgets should allow the investigator to extract needed information on the relevant processes. For example, in this study, data on landslide distributions were limited by the spatial resolution of traditional Landsat sensors. The newly available high resolution satellite data, and computers that can handle the high volume, could help address this deficiency. GIS and remote sensing technologies are clearly powerful tools that can aid the development of sediment budgets. However, overreliance on some of the new "sophisticated" technologies cannot replace basic process observations carried out in the field.

With respect to watershed research worldwide, many processes of basin denudation are rarely studied due to the inherent difficulties in setting up experiments. Until more is known about erosion processes between sediment entrainment at the soil erosion plot scale and sediment entry into channel systems, important parts of watershed sediment dynamics will remain poorly understood. Research is particularly needed on erosion and depositional processes beyond the hillslope plot and upslope of first order channels. In the tropics, soil erosion research has focused on cleared lands and on the effects of deforestation. More work is needed to obtain baseline data on geomorphological processes in natural forests.

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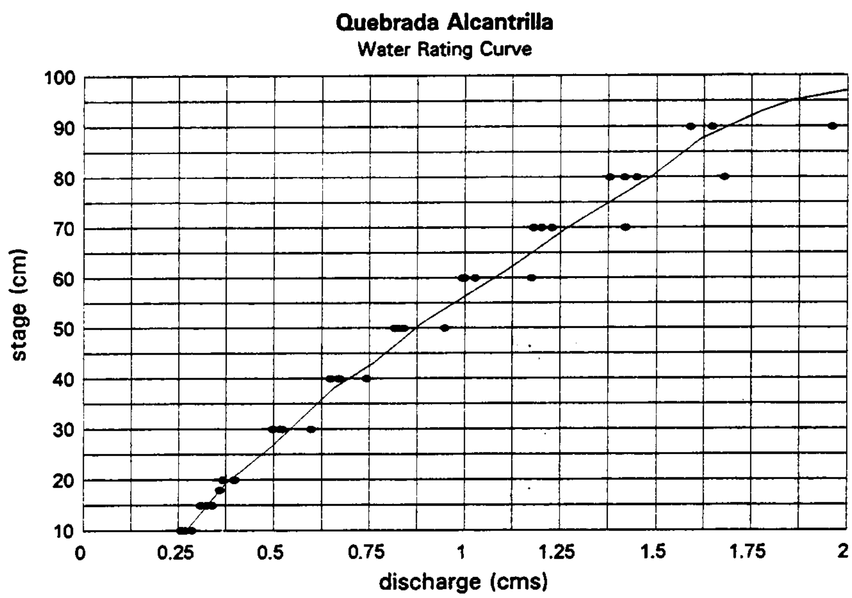
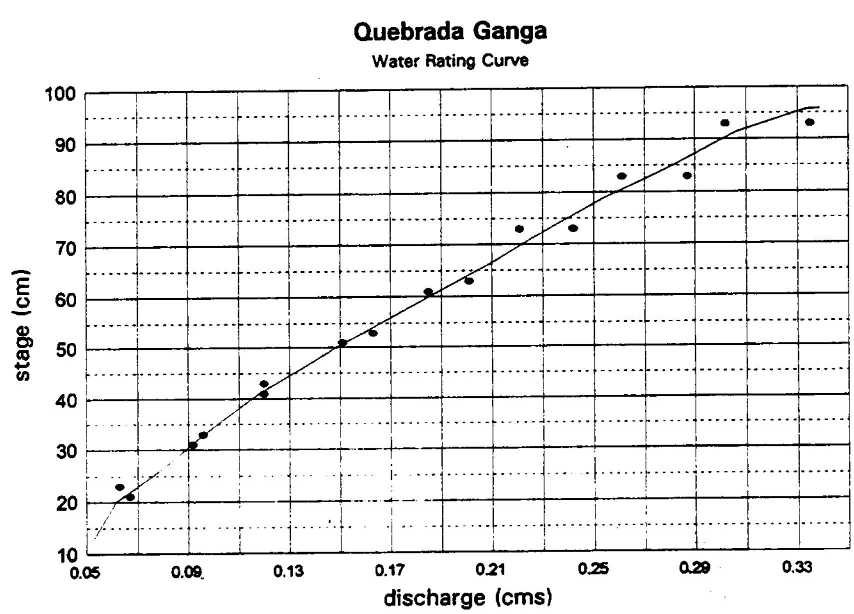
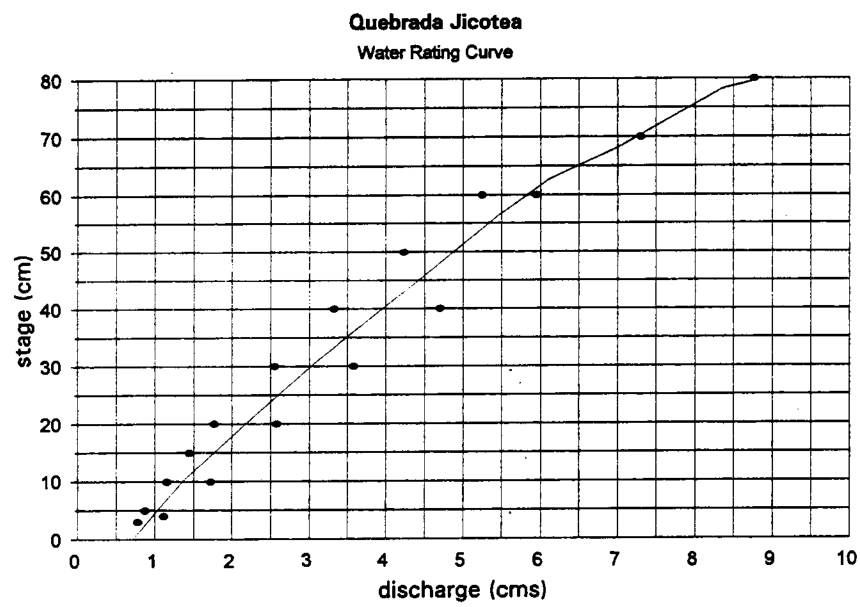
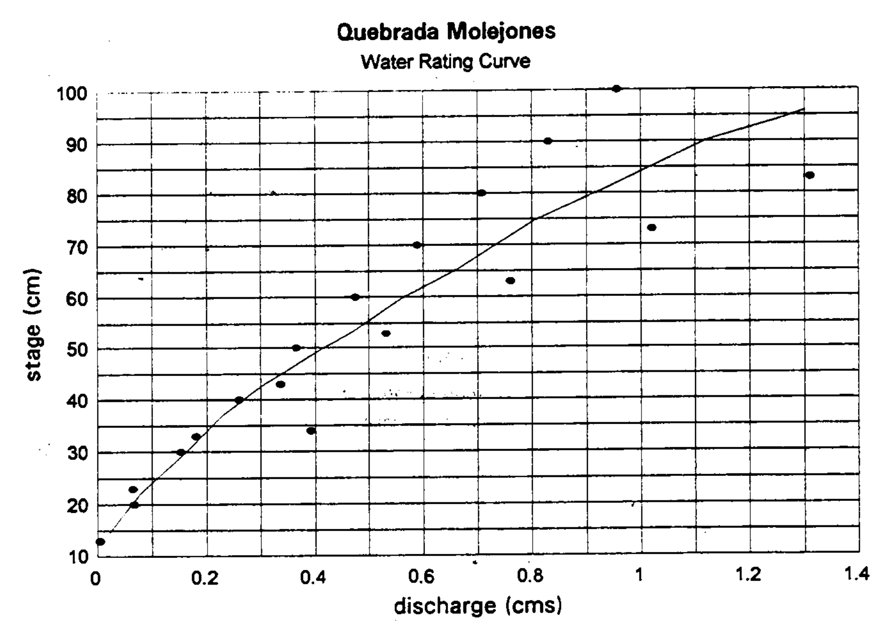
APPENDICES



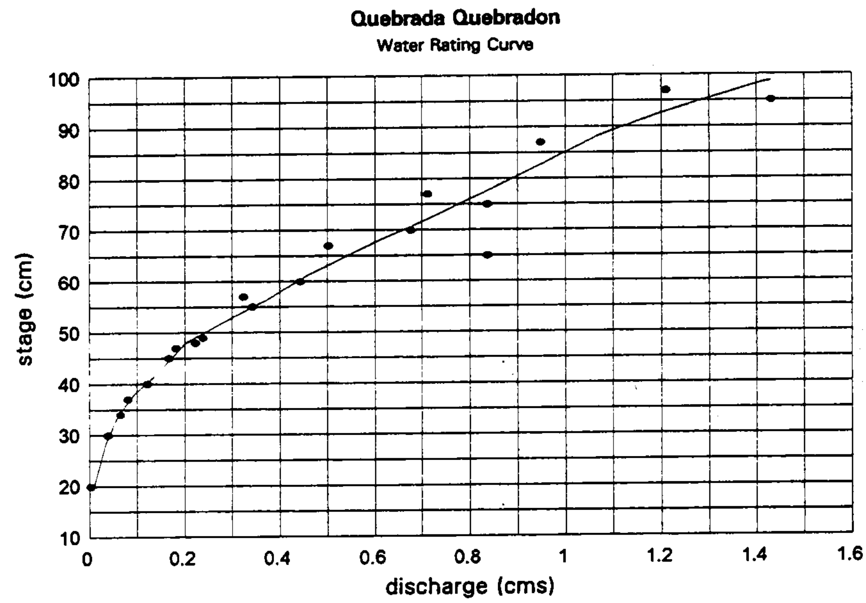


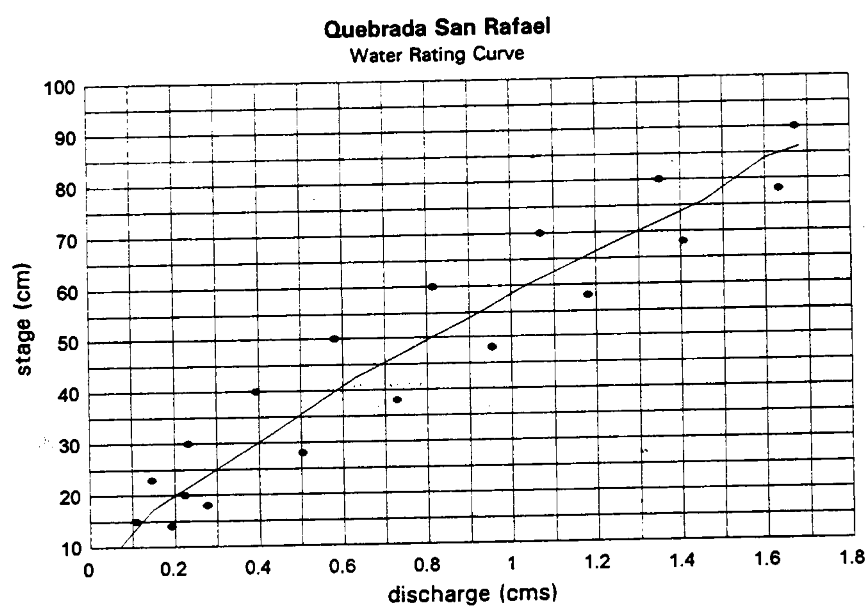
Appendix I. Water rating curves for tributary streams





Appendix I. Water rating curves for tributary streams, continued.





Appendix I. Water rating curves for tributary streams, continued.

Appendix 2. Tributary Stream Sediment Concentrations

tributary	stage	discharge cms	Q km^{-2}	mg l^{-1}	basin area km^2	analysis date month	day	year
Alcantrilla	34	0.625	0.056	260	11.19	4	13	95
Alcantrilla	46	0.82	0.073	215	11.19	4	13	95
Alcantrilla	38	0.68	0.061	162	11.19	4	13	95
Alcantrilla	34	0.625	0.056	2913	11.19	9	9	95
Alcantrilla	26	0.48	0.043	9010	11.19	9	9	95
Alcantrilla	29	0.54	0.048	34	11.19	4	13	95
Alcantrilla	46	0.82	0.073	13532	11.19	9	9	95
Alcantrilla	23	0.44	0.039	298	11.19	4	13	95
Alcantrilla	80	1.51	0.135	490	11.19	9	13	95
Alcantrilla	57	0.99	0.088	288	11.19	9	13	95
Ganga	45	0.175	0.034	509	5.14	9	13	95
Ganga	66	0.203	0.039	215	5.14	9	9	95
Ganga	73	0.222	0.043	451	5.14	9	13	95
Ganga	41	0.135	0.026	227	5.14	9	9	95
Ganga	40	0.165	0.032	118	5.14	9	9	95
Ganga	57	0.117	0.023	1401	5.14	4	13	95
Ganga	55	0.117	0.023	1293	5.14	4	13	95
Jicotea	59	5.57	0.283	3951	19.7	9	9	95
Jicotea	25	2.525	0.128	173	19.7	9	13	95
Jicotea	25	2.525	0.128	174	19.7	9	13	95
Jicotea	42	4.15	0.211	2257	19.7	9	9	95
Molejones	76	0.82	0.165	519	4.97	10	7	94
Molejones	83	0.92	0.185	4230	4.97	11	10	94
Molejones	52	0.46	0.093	5083	4.97	11	10	94
Molejones	78	0.835	0.168	347	4.97	11	10	94
Molejones	39	0.285	0.057	3	4.97	10	7	94
Molejones	39	0.285	0.057	3	4.97	10	7	94
Molejones	45	0.36	0.072	88	4.97	9	9	95
Molejones	62	0.605	0.122	48	4.97	10	7	94
Molejones	41	0.31	0.062	121	4.97	4	13	95
Molejones	31	0.19	0.038	55	4.97	4	13	95
Molejones	64	0.63	0.127	32302	4.97	9	9	95
Molejones	54	0.485	0.098	161	4.97	9	9	95
Molejones	45	0.36	0.072	12	4.97	11	10	94
Molejones	95	1.075	0.216	1285	4.97	9	13	95
Molejones	86	0.901	0.181	2149	4.97	9	13	95
Molejones	66	0.66	0.133	2740	4.97	9	13	95
Platanillo	31	0.98	0.164	11	5.98	11	10	94
Platanillo	43	1.375	0.230	104	5.98	12	12	94
Platanillo	50	1.6	0.268	1422	5.98	11	10	94

Appendix 2. Tributary Stream Sediment Concentrations, continued

tributary	stage	discharge cms	Q km^{-2}	mg l^{-1}	basin area km^2	analysis date month	day	year
Platanillo	31	0.98	0.164	10	5.98	11	10	94
Platanillo	85	3.06	0.512	1198	5.98	10	7	94
Platanillo	61	2.01	0.336	8651	5.98	10	7	94
Platanillo	28	0.88	0.147	2141	5.98	10	7	94
Platanillo	33	1.05	0.176	346	5.98	10	7	94
Platanillo	96	3.52	0.589	1329	5.98	10	7	94
Platanillo	41	1.3	0.217	686	5.98	11	10	94
Platanillo	69	2.38	0.398	705	5.98	11	10	94
Platanillo	65	2.18	0.365	3746	5.98	10	7	94
Platanillo	79	2.81	0.470	1961	5.98	10	7	94
Platanillo	50	1.6	0.268	8063	5.98	10	7	94
Platanillo	35	1.12	0.187	39	5.98	12	12	94
Platanillo	55	1.76	0.294	8114	5.98	12	12	94
Platanillo	83	2.97	0.497	6491	5.98	12	12	94
Platanillo	30	0.955	0.160	19592	5.98	4	13	95
Platanillo	46	1.46	0.244	5675	5.98	12	12	94
Platanillo	105	3.9	0.652	2093	5.98	12	12	94
Platanillo	45	1.44	0.241	261	5.98	12	12	94
Platanillo	30	0.955	0.160	1414	5.98	4	13	95
Platanillo	74	2.56	0.428	1370	5.98	12	12	94
Platanillo	36	1.14	0.191	219	5.98	4	13	95
Platanillo	36	1.14	0.191	36	5.98	12	12	94
Platanillo	38	1.23	0.206	35	5.98	12	12	94
Platanillo	38	1.23	0.206	23	5.98	12	12	94
Platanillo	28	0.88	0.147	62627	5.98	4	13	95
Platanillo	38	1.23	0.206	23	5.98	12	12	94
Quebradon	95	1.35	0.162	2248	8.33	9	13	95
Quebradon	77	0.065	0.008	4009	8.33	9	13	95
Quebradon	34	0.823	0.099	17	8.33	9	13	95
Quebradon	55	0.345	0.041	21910	8.33	12	12	94
Quebradon	67	0.523	0.063	2476	8.33	9	13	95
San Rafael	51	0.845	0.129	782	6.53	12	12	94
San Rafael	66	1.162	0.178	1609	6.53	10	7	94
San Rafael	45	0.725	0.111	6	6.53	12	12	94
San Rafael	40	0.62	0.095	605	6.53	12	12	94
San Rafael	48	0.78	0.119	2077	6.53	11	10	94
San Rafael	58	1.015	0.155	7191	6.53	11	10	94
San Rafael	66	1.162	0.178	5718	6.53	11	10	94
San Rafael	40	0.6	0.092	2275	6.53	11	10	94
San Rafael	42	0.65	0.100	1932	6.53	10	7	94
San Rafael	48	0.78	0.119	1626	6.53	10	7	94
San Rafael	58	1.015	0.155	33	6.53	12	12	94
San Rafael	72	1.28	0.196	1866	6.53	10	7	94

VITA

Glenn G. Hyman was born in Raleigh, North Carolina on October 17, 1962. He attended primary and secondary schools in Wake County, NC and graduated from Athens High School in 1981. He spent 2 years at Appalachian State University before transferring to the University of North Carolina at Chapel Hill where he received the Bachelor of Arts degree in International Studies in 1985. In 1988, he entered Appalachian State University and graduated with a Master of Arts in Geography in 1990. Mr. Hyman entered the doctoral program at the University of Tennessee in August 1990. With the support of a Fulbright scholarship he began his field work in Turrialba, Costa Rica in December 1992. During 1995 he worked as a consultant to the Watershed Management Department at the Centro Agronomico Tropical de Investigación y Enseñanza (CATIE) in Turrialba. He is presently a Visiting Scientist with the Land Management Group at the International Center for Tropical Agriculture (CIAT) in Cali, Colombia.